Discomfort Glare and Time of the Day

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Abstract

There are strong reasons to suspect that glare sensation varies with time of the day. This study was designed to test whether such a relationship exists. Thirty subjects were exposed to an artificial lighting source at four times of the day. The source luminance was progressively increased and subjects were required to give Glare Sensation Votes (GSVs) corresponding to the level of visual discomfort experienced. Glare indices were calculated for every reported GSV, and results were statistically analysed. The findings indicated a tendency towards greater tolerance to luminance increases in artificial lighting as the day progresses. This trend was found not to be statistically related to the possible confounding variable of learning, providing evidence of an effect of time of the day on glare sensation.

Keywords: Glare, Tolerance, Time of the Day, Controlled Experiment, Learning

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1. Introduction

Several indices have been published in the scientific literature and in international standards to describe the subjective perception of discomfort glare experienced by observers[1]. However, if a large number of subjects were asked to give their impression of visual sensation from different light sources characterised by similar glare indices, and votes were plotted on a graph, the results would show a large scatter[2]. This suggests that there is personal variability in the perceived level of visual discomfort, and that there could be other variables that influence glare sensation other than the four typically embedded in glare index formulas: 1) source luminance; 2) source size; 3) background luminance; and, 4) position index.

The following studies have investigated some of the additional factors that can potentially influence the subjective perception of discomfort glare, and that may be linked to the above mentioned scatter in plotted results.

In a laboratory experiment, Tuaycharoen and Tregenza (2005)[3] analysed the relationship between content of the view and perceived level of visual discomfort, finding that the information contained within an image judged as 'interesting' can influence the tolerance to discomfort glare. Further studies have shown that this effect is also present in a real window[4, 5].

A field study in office environments by Kuhn *et al.* (2013)[6] showed that glare was more frequently reported by older occupants, while Pulpitlova and Detkova (1993)[7] detected a higher tolerance to discomfort glare in Japanese rather than in European subjects. These findings suggest that there could be age and ethnical differences in visual perception.

The relationship between individual variation in light sensitivity (photophobic vs. photophilic subjects) and the occurrence of glare has also been investigated in the literature[8]. However, a controlled laboratory experiment found that differences in light sensitivity were not associated with the source luminance or source size. Rather, factors linked to the manifestation of glare phenomena were behavioural and task-related, for example due to continuous changes in position index[9].

The literature also shows that variables other than objective photometric quantities could be taken into account to predict the reported level of visual sensation.

Among others, in a field test Altomonte (2009)[10] found that, during early morning in winter, daylight exposure and contrast ratios from an East-facing office window could cause visual discomfort, although the occupant reported no glare and had no desire to close the venetian blinds. However, at the same time in summer, regardless of the absence of obvious glare sources, the blind was drawn by the user. An interview with the occupant revealed that, in winter, abundant morning daylight ingress was preferred to feel awake at the start of the day, while, in summer, sufficient luminous stimulation had already occurred before entering the office for triggering metabolic 'non-visual' processes, including neuroendocrine (i.e., melatonin suppression) and neurobehavioral (i.e., subjective alertness) responses[11]. The term 'non-visual' is utilised in this paper to refer to the relatively recent results of photobiological research that have demonstrated that lighting stimuli, other than providing vision and spatial/colour perception, have also a metabolic effect that regulates circadian processes and is responsible for hormonal regulation[12].

Nevertheless, not enough is yet known about the physiological and psychological basis of discomfort glare[13], nor 'subjective' variables have been consistently considered by standards and regulations, which are still largely based on conventional glare indices. Differences in visual response linked to temporal variables (e.g., seasonal, daily, and also on shorter time scale) are yet to be comprehensively investigated[14]. Indeed, no record was found in the literature of a systematic analysis of the effect of time of the day on the reported level of discomfort glare. However, there have been several studies looking at how light influences the non-visual system at different periods of the day.

Among these, Andersen *et al.* (2012)[15] showed that the non-visual effects of light can be either beneficial or detrimental depending on when the observer is exposed to the luminous source. Studies by Cajochen *et al.* (2000)[16], Zeitzer *et al.* (2000; 2005)[17, 18], and Phipps-Nelson *et al.* (2003)[19] indicated that the levels of illuminance at the eye required to trigger non-visual responses are significantly different between daytime and biological night. Mardaljevic *et al.* (2012)[20] proposed a framework built upon the literature, suggesting that – at various times of the day during the 24-hour cycle – different responses in the visual and metabolic systems are triggered from light exposure. In essence, the reviewed literature provides strong reasons to believe that the photoreceptive system responsible for metabolic stimulation presents changes over time. Although there is currently not sufficient evidence to demonstrate that the two systems are linked, it can be hypothesised that the visual discomfort system may exhibit similar temporal variations to the non-visual one. In response to this hypothesis, this study was set to investigate whether an effect of time of the day could be detected on the reported level of glare sensation.

2. Method

2.1 Experimental Setup

To answer the research question of this study, an experimental test was designed.

First of all, the four variables found in most conventional glare indices needed to be controlled. Then, all parameters that – from the literature – are alleged to influence discomfort glare, but are not included in glare index formulas, needed to be isolated. Along with this, all extraneous variables needed to be 'masked' within the experiment.

This was anticipated to reduce the large scatter found when evaluating subjective responses to discomfort glare, hence increasing the possibility of revealing factors that might influence glare sensation, but have not yet been tested.

In order to verify whether an effect of time of the day on the reported level of discomfort glare could be detected, a laboratory experiment under artificial lighting conditions was considered appropriate. This was based on the hypothesis that if the influence of time of the day on discomfort glare cannot be identified under controlled conditions, it is unlikely that this effect can be isolated using daylight from a real window, whereas several parameters would be continuously changing with time.

An initial pilot study involving eight subjects provided useful feedback to fine tune the experimental setup and methodology, and consolidate the research hypotheses.

The design of the apparatus (Figure 1) was informed by the study conducted by Tuaycharoen and Tregenza (2005)[3], which used this setup to investigate the influence of 'interest' of view on discomfort glare.

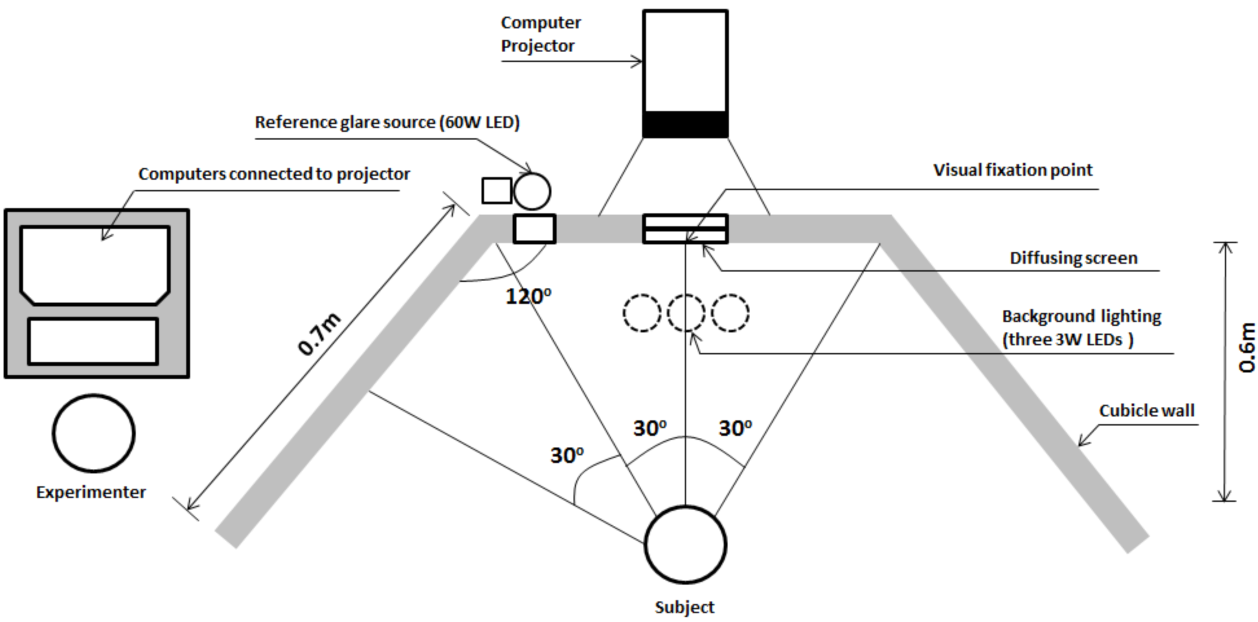

Figure 1. Layout of the Experimental Lighting Chamber

The chamber was semi-hexagonal in plan, the interior surfaces (2.7m in height) were painted matte white, and three 3W LED lamps, mounted from above, were used to produce 65cd/m^2 background lighting and maintain a constant luminance distribution.
The shape and size of the cubicle was designed to cover the entire field of view for binocular vision, spanning from 60^o left to 60^o right, and from 53^o above to 67^o below, relative to the line of sight[21]. The subjects' eye position was placed at a height of 1.2m from the floor and at the centre of the apparatus, facing two light sources: on the direct line of sight at the centre of the middle cubicle, a small diffusive screen made from two sheets of tracing paper (0.08 x 0.04m^2) was mounted in front of a projector connected to a computer; and, at an angle of 30^o to the left of the line of sight, a small reference glare source was located (60W LED). Considering that conventional glare indices for artificial lighting are designed to deal with small sources below 0.01 steradians[22], the projector created a condensed source of glare into the small diffusive screen, subtending an angle at the eye of 0.009 steradians and providing a variable luminance in the range between 400 cd/m^2 and 20,000 cd/m^2. The additional reference glare source was connected to a dimmer directly controlled by the subject. Experimental conditions were kept constant throughout the testing, with the only difference being represented by the variation of the luminance of the small diffusive screen.

2.2 Experimental Procedure

The experimental procedure was designed so that all parameters known to influence discomfort glare – i.e., source luminance and size, background luminance, position index, luminance distribution, visual task, view, and source uniformity – were controlled, while the testable variable (time of the day) was varied. Since no established methodology could be found in the literature to detect a potential effect of time of the day on the reported level of visual discomfort, the framework used by Mardaljevic *et al.* (2012)[20] to describe how the non-visual system responds to light was adopted for this experiment. The experimental procedure requested subjects to participate, on the same day, to four test sessions evenly distributed at 3-hours intervals:

- Morning: 09:00 or 09:30
- Afternoon A: 12:00 or 12:30
- Afternoon B: 15:00 or 15:30
- Evening: 18:00 or 18:30

Subjects could elect whether to participate to the sequence of test sessions starting at 09:00 or rather at 09:30. Conducting two sequences of experimental sessions per day allowed minimising the total testing time, therefore reducing the potential influence of seasonal changes in daily lighting patterns on visual response, which could become relevant when testing a large number of subjects. Besides, the pilot study had revealed no significant differences in results if intervals between test sessions were lower than 1.5 hours, thus a difference of 30 minutes between sessions was considered sufficiently guarded from any temporal discrepancy in collecting results from different subjects.

An interval of 3 hours between test sessions was deemed adequate to monitor the response of subjects on a free-running day and prevent disruption from the subjects' daily routine, which could potentially influence glare response. However, it was contemplated that maintaining the same sequence of test sessions for all subjects could potentially mask an effect of learning into the design procedure. Indeed, Hopkinson (1950)[23] hypothesised that a less experienced subject could not be able to interpret in a consistent manner the meaning of discomfort glare descriptors. To address this issue, a follow-up study to the main experiment was designed and conducted in order to ascertain the eventual influence of learning on the results obtained.

According to the literature, discomfort glare is a personal sensation that requires subjective evaluation methods[24]. Therefore, during the tests, subjects were asked to make judgements of glare sensation utilising as benchmarks adaptations of the Glare Sensation Votes (GSVs) used by Iwata *et al.* (1992a; 1992b)[25, 26], Iwata and Tokura (1998)[27] and Mochizuki *et al.* (2009)[28]. These are glare indices corresponding to a sensation of visual discomfort that subjects experience: 'Just Perceptible', 'Just Noticeable', 'Just Uncomfortable', and 'Just Intolerable'. Since it was considered that each criterion could be open to self-interpretation due to the abstraction caused by the assessment – and potentially increase scattering of responses – to aid subjects giving more meaningful judgements, the GSVs criteria were linked with time-span descriptors[22].

At the beginning of the test, the subject was asked to adjust the stool so that the head was properly located at the viewing position. A clear set of instructions was then given, including a definition of discomfort glare, the meaning of the four GSV criteria, and a description of how the experiment would run. To confirm that subjects had a proper understanding of the four GSV criteria, they were asked to look at the reference glare source and to adjust its brightness by using a dimmer located by their seat, so that the glare sensation produced was assessed as, progressively, 'Just Perceptible', 'Just Noticeable', 'Just Uncomfortable' and 'Just Intolerable'. The subject was then asked to direct the gaze towards a fixation point located at the centre of the small diffusive screen and to imagine that this represented a visual task in the field of view. The luminance of the screen was then incrementally increased, at a controlled and constant pace, by the experimenter via a computer connected to the projector. Throughout the procedure, the subject was asked to vocally indicate when the sensation of discomfort glare due to the brightness of the diffusive screen became, respectively, 'Just Perceptible', 'Just Noticeable', 'Just Uncomfortable' and 'Just Intolerable'. The photometric values at which each GSV occurred were recorded. Each test session lasted around 10 minutes.

2.3 Photometric Measurements and Glare Indices

Before the start of the experiments, photometric measurements were taken from the subjects' eye position using a Minolta LS-110 mounted on a tripod. The mean background luminance was calculated from 17 individual measurements taken on a regular grid symmetrical about the central fixation point and extending across the width of the cubicle. The mean background luminance was held at 65cd/m^2 throughout the experiment, since this value is within the range commonly found in interior spaces[29].

The luminance of the small diffusive screen was evaluated using point measurements. The source luminance was progressively increased using the relative brightness function of an image editing software, which was operated from a computer linked to the projector. In order to achieve precise luminance outputs in repeated procedures, the projector had to be calibrated. The relative brightness was adjusted at evenly distributed intervals and spot point measurements were taken at each interval. Luminance values were then interpolated using a polynomial function to obtain values between the calibrated luminance data points.

To be consistent with the literature[1, 2] and the described experimental design, glare indices were used in this study as primary evaluation parameters. Among others, Tuaycharoen and Tregenza (2005; 2007)[3, 4] used the Unified Glare Rating (UGR) and the Glare Index (GI) to test the hypothesis that bright images that subjects find interesting are associated with a lower degree of discomfort glare than other sources with the same glare index. In this paper, the IES-GI – a glare formula commonly found in lighting codes (1)[30, 31] – has been used to objectively quantify subjective assessments of discomfort glare from an artificial lighting source. Results were calculated also utilising the UGR glare index formula (2) and they were found to follow the same trends of the IES-GI. For this reason, results obtained using the UGR have not been reported in this paper.

(1) $$\mathbf{IES\text{–}GI} = \mathbf{10Log_{10} 0.478} \sum \left(\frac{L_s^{1.6} \cdot \omega^{0.8}}{L_b \cdot P^{1.6}} \right)$$

(2) $$\mathbf{UGR} = \mathbf{8Log_{10}} \left(\frac{0.25}{L_b} \sum \frac{L_s^2 \cdot \omega}{P^2} \right)$$

whereby,

L_s is the source luminance (cd/m^2)
L_b is the background luminance (cd/m^2)
ω is the subtended size of the source (sr)
P is the position index

Both the IES-GI and the UGR carry high, although differently weighted, exponentials for source luminance, a parameter that has been very strongly correlated to the experience of glare sensation ($p< 0.001$)[9]. The sensitivity of these glare indices to changes in source luminance makes them suitable to detect the effect of time of the day in the experiment. In fact, since glare indices are well-tested tools, any variability within the index corresponding to the GSVs provided by subjects will show justification that there is a factor, other than the parameters embedded within the formula itself, which is influencing glare sensation.

3. Results and Discussion

3.1 Experiment I: Discomfort Glare and Time of the Day

A total of 30 test subjects volunteered to take part to the experiment. Membership to the group was tightly controlled. All participants were 5th year architecture students, 17 men and 13 women, the mean age was 24.10 (SD = 3.21), 10 wore corrective lens, 2 stated not to have normal colour vision, and 6 reported vision problems. Figures 2 to 5 plot on the y-axis the log luminance (cd/m^2) of the small diffusive screen at which each subject reported glare sensation votes (GSV) of, respectively, 'Just Perceptible' (Fig. 2), 'Just Noticeable' (Fig. 3), 'Just Uncomfortable' (Fig. 4) and 'Just Intolerable' (Fig. 5). On the x-axis, the figures present the test sessions corresponding to the time of the day at which votes of glare sensation were reported. In Figures 2 and 3, the ID numbers of individual test subjects are indicated next to outliers and extreme scores. For all Figures, there is a tendency for the statistical values (e.g., 25th Percentile, Median, 75th Percentile) to correspond to higher levels of source luminance as the day progresses.

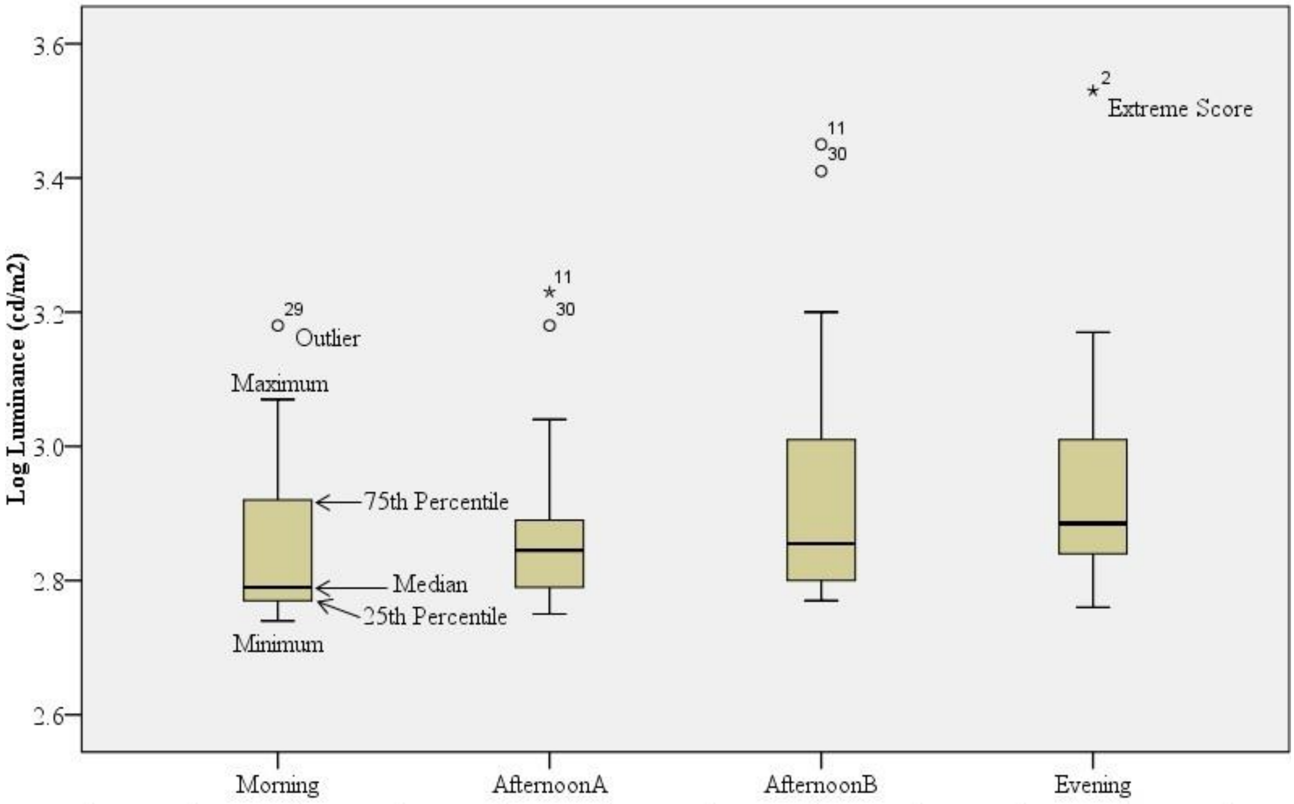

Figure 2. Boxplot of results for 'Just Perceptible'

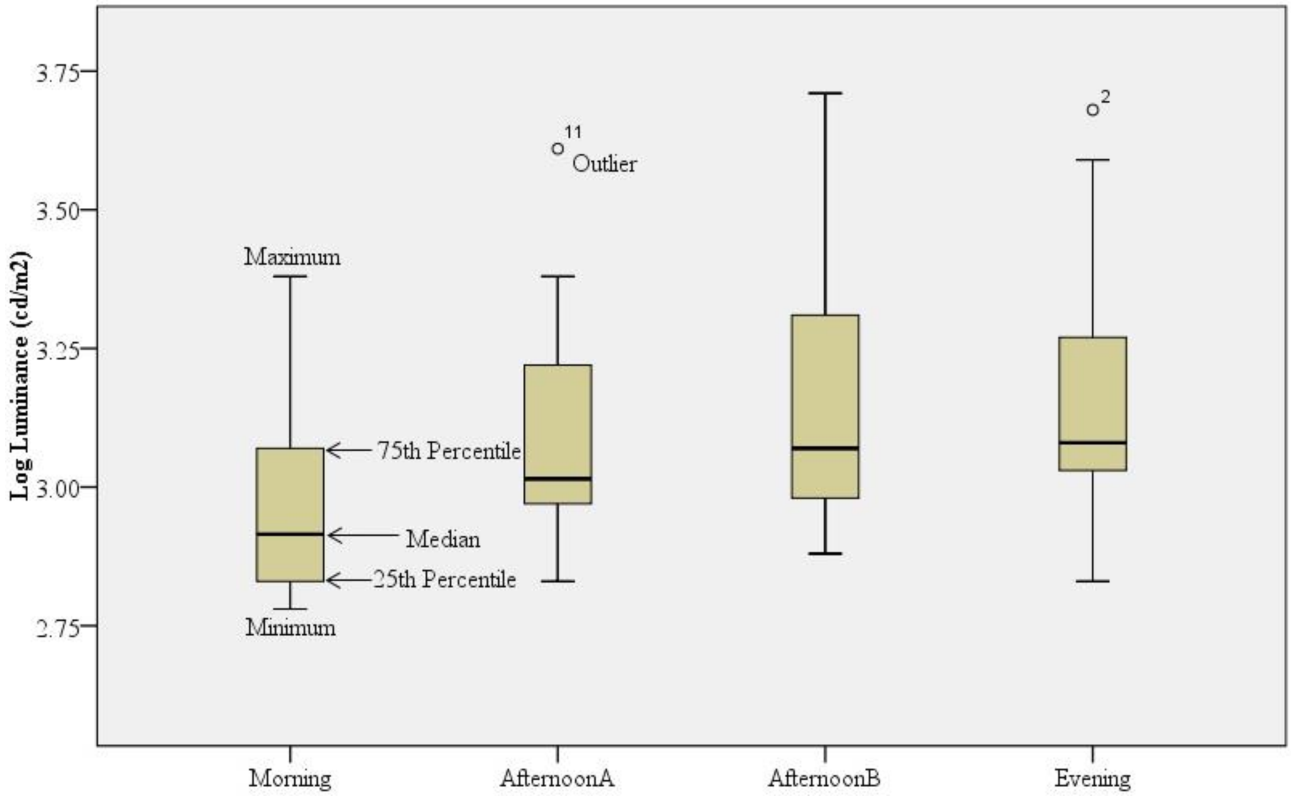

Figure 3. Boxplot of results for 'Just Noticeable'

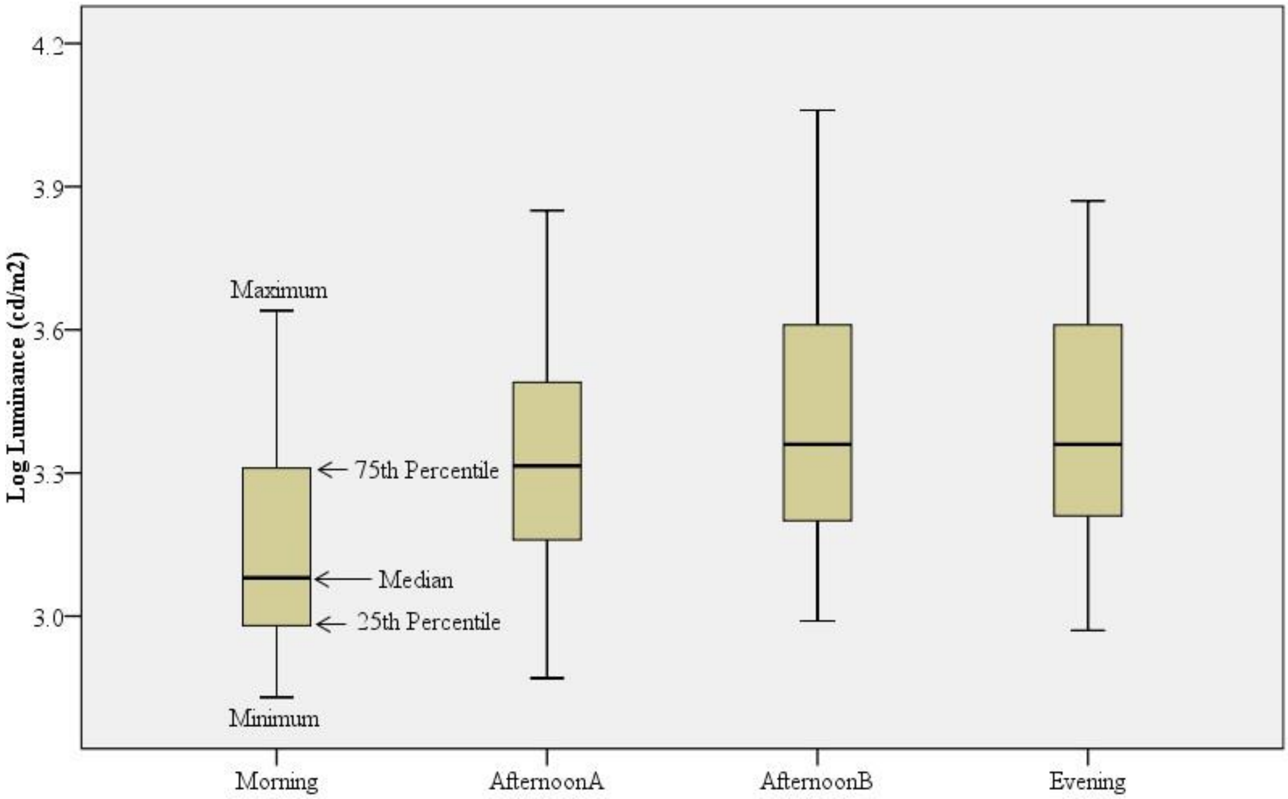

Figure 4. Boxplot of results for 'Just Uncomfortable'

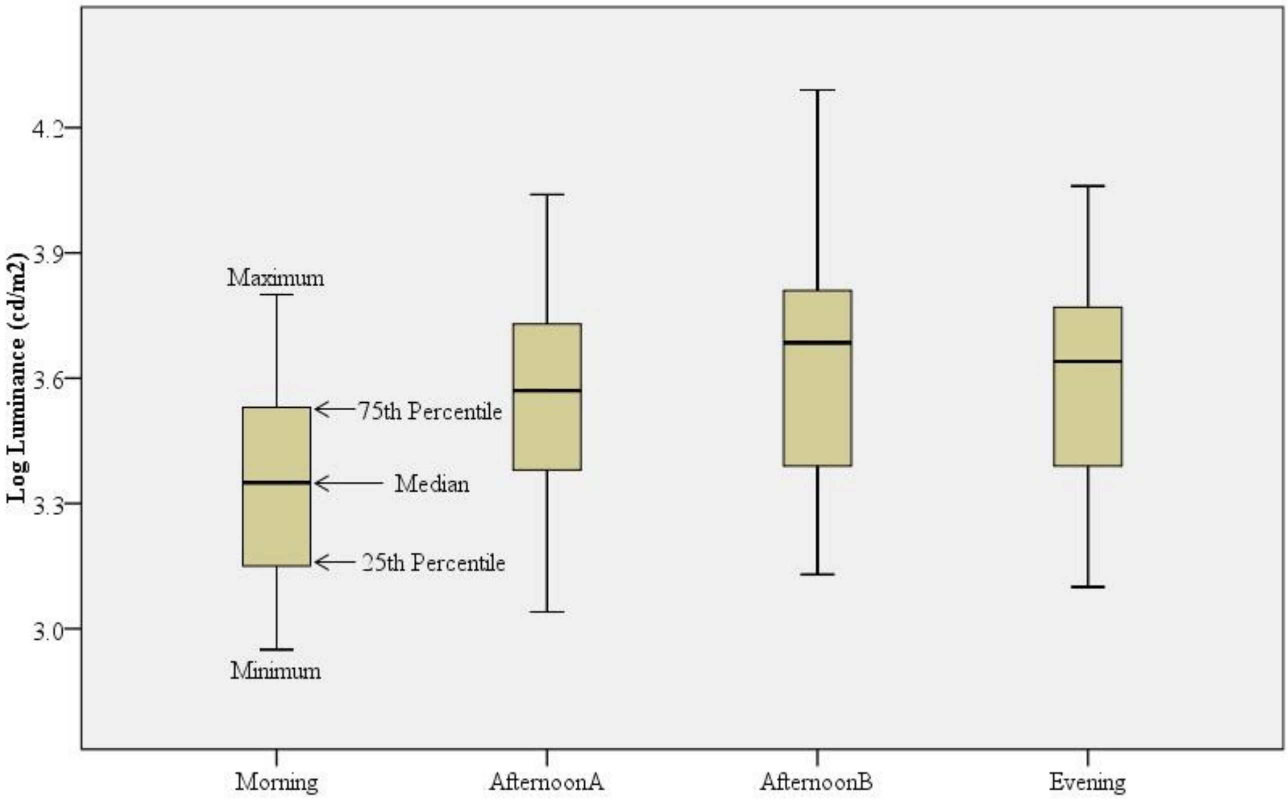

Figure 5. Boxplot of results for 'Just Intolerable'

Both the IES-GI and UGR glare indices corresponding to the luminance values at each GSV reported by test subjects were calculated for each time of the day. Null Hypothesis Significance Testing (NHST) was performed to determine if differences between independent groups could be due to chance or to an accident in sampling. To analyse the data, a Friedman's analysis of variance (ANOVA) was initially run to compare the glare indices for each GSV at all four sessions against each other. This test was used since graphical (e.g., Q-Q plot) and statistical inspection (e.g., Shapiro-Wilk and Kolmogorov–Smirnov tests) of the data revealed that sampling distributions around the mean were not normally distributed, hence violating one of the assumptions for a parametric test[32]. For the IES-GI, the Friedman's ANOVA detected highly significant differences: 'Just Perceptible', $\chi^2(2)= 29.60$, $p< .000$; 'Just Noticeable'; $\chi^2(2)= 31.79$, $p< .000$; 'Just Uncomfortable', $\chi^2(2)= 30.97$, $p< .000$; and 'Just Intolerable', $\chi^2(2)= 19.79$, $p< .000$. Similar highly significant differences were found for the UGR glare index, and are therefore not herein reported.

A post-hoc analysis was then performed whereby all permutations between times of the day were compared against each other, and the statistical significance of the differences were calculated using a one-tailed Wilcoxon Matched Pairs test to determine exactly where the variations detected in the Friedman's ANOVA were. The Wilcoxon Matched Pairs test of significance was one-tailed since the testable hypothesis consisted in verifying whether the perceived level of glare sensation triggered by the source luminance decreased at later stages of the day. The directionality of this hypothesis derived from the analysis of the results of the initial pilot study, which – under a two-tailed test – suggested a trend for an increased tolerance to discomfort glare as the day progresses. The experiment was blinded with respect to the testable hypothesis in both the pilot study and in the main experiment. That is, although participants were informed that they were required to attend multiple test sessions at different times of the day, they were not aware of the full aim of the study.

To counterbalance the experiment wise error rate caused by the significance level inflating across multiple pairwise comparisons – which was calculated as: $1 - (0.95)^n = 0.26$ (thus risking a 26% probability of making at least one Type I error), whereby n= 6, i.e. the number of Wilcoxon tests carried out on the same data[33] – Bonferroni corrections were applied. For each statistical test, the effect size was also calculated. There are indeed several limitations with using Null Hypothesis Significance Testing to infer the size (or relative impact) of the differences between sample groups. The main one is that the *p*-value depends both on the size of the effect and on the size of the sample[34]. Conversely, by placing the emphasis on the most important aspect of the analysis – that is, the size of the effect (i.e., a standardised measure of the magnitude of the observed difference between sample groups) and not just its statistical significance (which confounds effect size and sample size) – the effect size shows if the predictor variable has any practical significance and thus provides a more rigorous support to inferences[35, 36]. In this study, the effect size was calculated by making use of equivalence between the standardised measure of the observed difference and the Pearson's coefficient *r*, extracting the z_{score} test-statistic from the Wilcoxon tests according to the following formula[33] (3):

$$\textbf{(3)} \qquad \boldsymbol{Effect\ Size = \frac{Z\ Score}{\sqrt{N}}}$$

whereby,

N is the number of observations

The interpretation of the outcome was derived from the tables provided by Ferguson (2009)[37], where conventional values have been proposed as benchmarks for 'small' (RMPE, recommended minimum effect size representing a practically significant effect), 'moderate', and 'strong' effects sizes ($r \geq 0.20$, 0.50, and 0.80, respectively). Tables 1-4 report the mean and standard deviation for the IES-GI glare index – calculated basing on the lighting values recorded when a GSV was reported by the test subjects – for all times of the day, the differences (ΔM) between the means for each pairwise comparison and their statistical significance, the effect size, the ranks for (positive) and against (negative) the hypothesis, and the ties.

Table 1. Wilcoxon Matched Pairs test and Effect Size for 'Just Perceptible'

Time of Day	Mean (SD)	Mean (SD)	ΔM	Effect Size	P Ranks	N Ranks	Ties
Aft. A vs. Morn.	8.16 (1.59)	7.88 (1.85)	0.28 n.s.	0.27	21	8	1
Aft. B vs. Morn.	8.91 (2.52)	7.88 (1.85)	1.03*	0.43	23	6	1
Even. vs. Morn.	9.45 (2.57)	7.88 (1.85)	1.57**	0.56	26	4	0
Aft. B vs. Aft. A	8.91 (2.52)	8.16 (1.59)	0.75*	0.44	18	8	4
Even. vs. Aft. A	9.45 (2.57)	8.16 (1.59)	1.29***	0.66	24	5	1
Even. vs. Aft. B	9.45 (2.57)	8.91 (2.52)	0.54 n.s.	0.33	18	10	2

With Bonferroni correction: *$p \leq 0.008$; **$p \leq 0.0016$; ***$p \leq 0.00016$; n.s. not significant

Table 2. Wilcoxon Matched Pairs test and Effect Size for 'Just Noticeable'

Time of Day	Mean (SD)	Mean (SD)	ΔM	Effect Size	P Ranks	N Ranks	Ties
Aft. A vs. Morn.	11.24 (2.70)	9.97 (2.86)	1.27*	0.48	24	5	1
Aft. B vs. Morn.	12.50 (3.27)	9.97 (2.86)	2.53***	0.68	25	5	0
Even. vs. Morn.	12.88 (3.26)	9.97 (2.86)	2.91***	0.69	25	5	0

Aft. B vs. Aft. A	12.50 (3.27)	11.24 (2.70)	1.26*	0.53	21	9	0
Even. vs. Aft. A	12.88 (3.26)	11.24 (2.70)	1.64*	0.52	23	6	1
Even. vs. Aft. B	12.88 (3.26)	12.50 (3.27)	0.38 n.s.	0.23	19	9	2

With Bonferroni correction: *p≤0.008; **p≤0.0016; ***p≤0.00016; n.s. not significant

Table 3. Wilcoxon Matched Pairs test and Effect Size for 'Just Uncomfortable'

Time of Day	Mean (SD)	Mean (SD)	ΔM	Effect Size	P Ranks	N Ranks	Ties
Aft. A vs. Morn.	15.13 (3.42)	12.45 (3.23)	2.68***	0.66	25	5	0
Aft. B vs. Morn.	16.58 (4.18)	12.45 (3.23)	4.13***	0.75	26	4	0
Even. vs. Morn.	16.52 (3.79)	12.45 (3.23)	4.07***	0.74	26	4	0
Aft. B vs. Aft. A	16.58 (4.18)	15.13 (3.42)	1.45*	0.46	21	9	0
Even. vs. Aft. A	16.52 (3.79)	15.13 (3.42)	1.39 n.s.	0.35	18	10	2
Even. vs. Aft. B	16.52 (3.79)	16.58 (4.18)	-0.06 n.s.	0.08	17	13	0

With Bonferroni correction: *p≤0.008; **p≤0.0016; ***p≤0.00016; n.s. not significant

Table 4. Wilcoxon Matched Pairs test and Effect Size for 'Just Intolerable'

Time of Day	Mean (SD)	Mean (SD)	ΔM	Effect Size	P Ranks	N Ranks	Ties
Aft. A vs. Morn.	18.99 (3.88)	15.97 (3.62)	3.02***	0.62	23	7	0
Aft. B vs. Morn.	20.45 (4.51)	15.97 (3.62)	4.48***	0.75	24	6	0
Even. vs. Morn.	20.02 (4.22)	15.97 (3.62)	4.05***	0.72	24	6	0
Aft. B vs. Aft. A	20.45 (4.51)	18.99 (3.88)	1.46*	0.46	19	11	0
Even. vs. Aft. A	20.02 (4.22)	18.99 (3.88)	1.03 n.s.	0.27	16	13	1
Even. vs. Aft. B	20.02 (4.22)	20.45 (4.51)	-0.43 n.s.	0.14	12	16	2

With Bonferroni correction: *p≤0.008; **p≤0.0016; ***p≤0.00016; n.s. not significant

The results indicate that the IES-GI glare index shows a tendency to increase at later times of the day. The Wilcoxon Matched Pairs tests provide evidence that the differences between glare indices calculated at different times of the day are highly significant (*p*≤ 0.00016) in 9 out of 24 cases, significant (p≤ 0.0016) in 1 case, weakly significant (p≤ 0.008) in 7 cases, and not significant in 7 cases. The differences detected have a generally substantive effect size, mostly ranging between 'moderate' (0.50 ≤ r < 0.80 in 12 cases out of 24) and 'small' (0.20 ≤ r < 0.50 in 10 cases out of 24)[37]. For the GSV criteria of 'Just Perceptible' and 'Just Noticeable', the data indicate that the differences in the IES-GI glare index increase when looking at variations between earlier and later times of the day. As an example, for the criterion of 'Just Noticeable' (Table 2), Afternoon A vs. Morning: Afternoon A, M= 11.24; Morning, M= 9.97; ΔM= 1.27; p≤ 0.008; r= 0.48. Afternoon B vs. Morning: Afternoon B, M= 12.50; Morning, M= 9.97; ΔM= 2.53; p≤ 0.00016; r= 0.68. Evening vs. Morning: Evening, M= 12.88; Morning, M= 9.97; ΔM= 2.91; p≤ 0.00016; r= 0.69. Analogous trends are also recognisable for the UGR glare index (not reported in the Tables). Similarly, at a higher degree of visual discomfort – corresponding to the GSV criteria of 'Just Uncomfortable' and 'Just Intolerable' – the largest influences of time of the day appear when comparing the Afternoon B and Morning sessions. As an example, for the criterion of 'Just Intolerable' (Table 4): Afternoon B, M= 20.45; Morning, M= 15.97; ΔM= 4.48, p≤ 0.00016, r = 0.75. Also in this case, both glare indices show equivalent tendencies. Therefore, from the statistical analysis of data, it can be inferred that the effect of time of the day on the sensation of discomfort glare is not uniform across the various GSV criteria of perceived visual discomfort. The statistical significance of variations and the effect sizes indicate that the differences appear to be more substantive when considering a larger time gap between sessions.

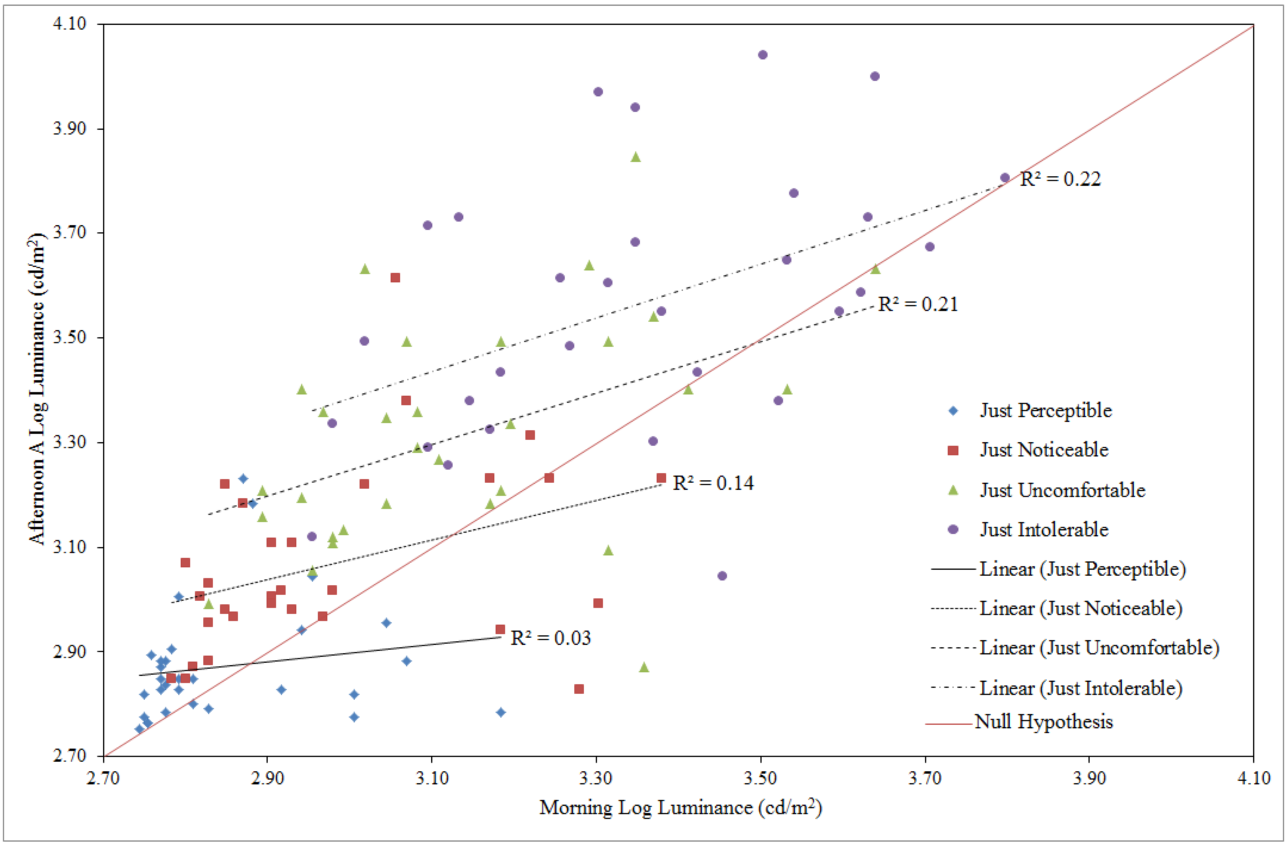

Figure 6. Comparison of results between the Morning and Afternoon A sessions

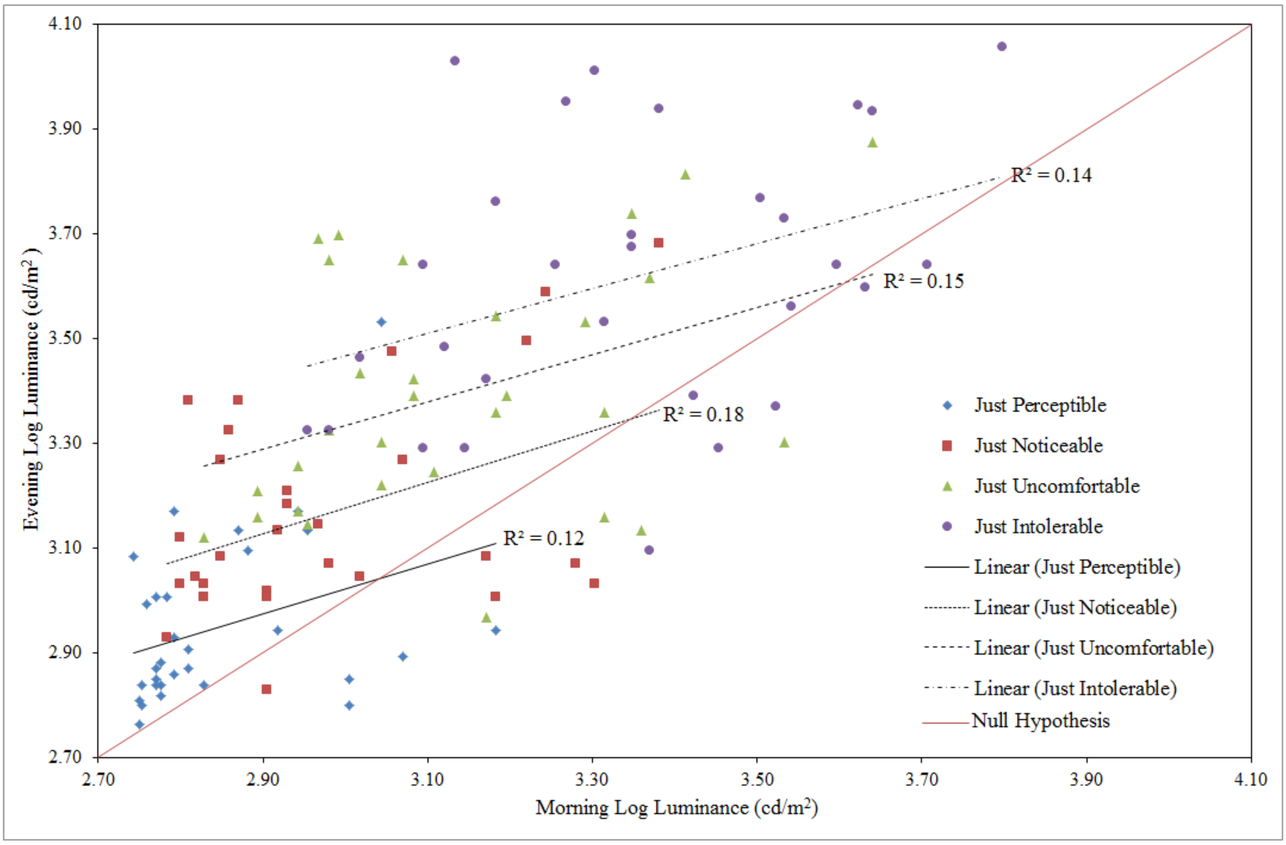

Figure 7. Comparison of results between the Morning and Evening sessions

Figure 6 and 7 plot the logarithmic luminance (cd/m^2) of the small diffusive screen at which each subject reported the various criteria of GSV, respectively in the Morning (x-axis) and Afternoon A (y-axis) sessions (Figure 6), and in the Morning (x-axis) and Evening (y-axis) sessions (Figure 7). For both Figures, the null hypothesis line is plotted along the diagonal of the graph, representing no difference between the source luminance corresponding to each GSV criterion reported by subjects at each session.

With reference to Figure 7, although some GSV points are below the null hypothesis line – indicating higher luminance values for some subjects in the Morning session – the interpolated lines for each criterion of GSV are above it, and at a larger distance from the null hypothesis line than those reported in Figure 6. This suggests that subjects were able to tolerate higher levels of luminance in the Evening than in the Morning session, and with a larger difference in source luminance than that detected when comparing the Afternoon A to the Morning session.

3.2 Experiment II: Time of the Day and Learning

The first experiment was by no means protected from any learning effect, i.e. it would be plausible hypothesising that subjects became more tolerant to glare with experience due to the sequence of the test sessions. For example, during the Morning session, subjects could have felt more anxious for the test, which may have made them more sensitive to the luminous stimulus.

Although the pre-test procedure that each participant was asked to complete – whereas test subjects looked at a reference glare source, adjusting by a dimmer its luminance output – clearly minimised this risk, a follow-up experiment was designed to investigate whether the 3-hour interval between sessions masked the influence of learning, and to determine if differences in glare sensation vote could be detected over two consecutive days using the same test subject. To be consistent with the first experiment, repeated test procedures were used.

A randomised design was rejected because of the impracticality of recruiting participants under a shuffled session sequence over multiple days and at variable times. The experimental setting and test procedure were thus identical to the first experiment.

Eight subjects volunteered to take part to this experiment, all doctoral students, varying in age, cultural background, and nationality. Each participant attended the original test sequence of four sessions equally spaced at 3-hours intervals on a chosen day, and then the same procedure was repeated on a successive day. The timing of the sessions was as follows: Morning (09:00 or 09.30), Afternoon A (12:00 or 12:30), Afternoon B (15:00 or 15:30); Evening (18:00 or 18:30). Even in this case, subjects could choose to participate to the sequence of test sessions starting at 09:00 or at 09:30.

To counterbalance the influence of confounding variables between the two days, fatigue, sleepiness, and metabolic stimulation (e.g., ingestion of food or caffeine), were recorded through self-reporting scales and questionnaires. On the basis of analogous results obtained in the first series of tests for the two glare indices, only the IES-GI was considered in this second experiment.

The IES-GI index was calculated in correspondence to each GSV given by the test subjects at the four times of the day. Consistently with the previous experiment, descriptive statistics showed a tendency for each GSV criterion to be reported at higher source luminance levels as the day progressed on both Day 1 and Day 2.

To examine the effect of learning, for all subjects the differences in GSVs over each test session were calculated on both days, and then compared across the two days. In other terms, statistical testing was performed so as to measure whether similar variations in tolerance to visual discomfort due to time of the day could be detected over two days. For this experiment, only three differences between sessions were considered, i.e.: Afternoon A vs. Morning; Afternoon B vs. Afternoon A; and, Evening vs. Afternoon B.

Unlike the first experiment, a graphical and statistical inspection of the data revealed that the assumptions of normality of the sampling distributions and the homogeneity of variance were not violated[32]. Thus, parametric methods of analysis could be adopted for this study, also leading to more powerful tests than their non-parametric counterparts[38].

To make the analysis more sensitive in detecting the effect of experimental interest – i.e., the potential influence of learning in subjective responses to visual discomfort over several sessions on two consecutive days – an analysis of covariance (ANCOVA) was selected since confounding variables could not be controlled over the independent variable[33].

In particular, across the two days of testing participants frequently indicated different levels of fatigue, which was self-reported by subjects at each test session on a continuous analogue scale. Tests of homogeneity of regression slopes between the dependent variable (glare) and the covariate (fatigue) – that is, the covariate has to have the same correlation with the dependent variable over the independent variable (time of the day)[33] – showed that this assumption was not violated.

Tables 6-9 show, for every GSV criterion, the adjusted mean (M) and standard deviation (SD) of the variations of the IES-GI index between the test sessions considered on each of the two days, the difference between the means obtained in Day 1 and in Day 2 (ΔM), the test statistic (F), the significance level (*p*-value) and the effect size in the form of partial-eta square ($p\eta^2$), which represents the variance explained by the dependent variable and by the covariate that is not explained by other variables in the analysis. Again, the interpretation of the outcome was derived from Ferguson (2009)[37], whereby conventional benchmarks have been proposed for 'small', ‘moderate’, and ‘strong’ effects sizes ($p\eta^2 \geq$ 0.04, 0.25, and 0.64, respectively).

Table 6. ANCOVA for ‘Just Perceptible’

Time of the Day	(M) Day 1 (SD)	(M) Day 2 (SD)	ΔM (Day 1-2)	F (df)	*p*-value	$p\eta^2$
Aft. A vs. Morn.	0.77 (2.34)	1.70 (2.14)	-0.93	0.81 (1,13)	0.39 n.s.	0.06
			Covariate	3.01 (1,13)	0.11 n.s.	0.19
Aft. B vs. Aft. A	0.97 (1.64)	1.75 (0.61)	-0.78	0.88 (1,13)	0.37 n.s.	0.06
			Covariate	1.91 (1,13)	0.19 n.s.	0.13
Even. vs. Aft. B	1.15 (2.08)	0.30 (2.21)	0.85	0.58 (1,13)	0.46 n.s.	0.04
			Covariate	0.05 (1,13)	0.46 n.s.	0.00

Table 7. ANCOVA for ‘Just Noticeable’

Time of the Day	(M) Day 1 (SD)	(M) Day 2 (SD)	ΔM (Day 1-2)	F (df)	*p*-value	$p\eta^2$
Aft. A vs. Morn.	1.22 (2.60)	2.17 (1.67)	-0.95	0.69 (1,13)	0.42 n.s.	0.05
			Covariate	1.33 (1,13)	0.27 n.s.	0.09
Aft. B vs. Aft. A	0.81 (2.32)	0.04 (1.76)	0.77	0.64 (1,13)	0.44 n.s.	0.05
			Covariate	3.49 (1,13)	0.08 n.s.	0.21
Even. vs. Aft. B	1.32 (1.50)	2.06 (1.58)	-0.74	0.39 (1,13)	0.54 n.s.	0.03
			Covariate	0.70 (1,13)	0.42 n.s.	0.05

Table 8. ANCOVA for 'Just Uncomfortable'

Time of the Day	(M) Day 1 (SD)	(M) Day 2 (SD)	ΔM (Day 1-2)	F (df)	*p*-value	$p\eta^2$
Aft. A vs. Morn.	1.09 (3.20)	2.47 (2.51)	-1.23	1.23 (1,13)	0.23 n.s.	0.09
			Covariate	0.00 (1,13)	0.96 n.s.	0.00
Aft. B vs. Aft. A	1.20 (2.88)	2.36 (1.07)	-0.77	0.90 (1,13)	0.36 n.s.	0.07
			Covariate	1.16 (1,13)	0.30 n.s.	0.08
Even. vs. Aft. B	1.13 (1.75)	2.43 (1.90)	-0.74	1.13 (1,13)	0.31 n.s.	0.08
			Covariate	0.53 (1,13)	0.48 n.s.	0.04

Table 9. ANCOVA for 'Just Intolerable'

Time of the Day	(M) Day 1 (SD)	(M) Day 2 (SD)	ΔM (Day 1-2)	F (df)	*p*-value	$p\eta^2$
Aft. A vs. Morn.	0.94 (3.45)	1.86 (2.19)	-0.92	0.49 (1,13)	0.50 n.s.	0.04
			Covariate	0.01 (1,13)	0.95 n.s.	0.00
Aft. B vs. Aft. A	1.00 (3.89)	1.80 (1.65)	-0.80	0.37 (1,13)	0.56 n.s.	0.03
			Covariate	0.21 (1,13)	0.65 n.s.	0.02
Even. vs. Aft. B	0.93 (1.56)	1.87 (2.58)	-0.94	0.51 (1,13)	0.49 n.s.	0.04
			Covariate	0.03 (1,13)	0.86 n.s.	0.00

Visual inspection of the descriptive statistics data reveals that a general tendency towards larger variations of glare indices between the test sessions can be detected on Day 2, resulting in predominantly negative ΔM values between the two days, particularly at higher levels of visual discomfort ('Just Uncomfortable' and 'Just Intolerable'). The inferential statistics show that the differences detected are, for all comparisons considered, not statistically significant ($p > 0.05$), although this could have possibly resulted from a small sample size. However, calculation of effect sizes indicates that the practical relevance of the variations detected for the dependent variable (glare) is negligible ($p\eta^2 < 0.04$) in 2 cases, and very small ($p\eta^2 \leq 0.09$) in 10 out of 12 cases. The larger effect sizes for the covariate (fatigue) are observed at lower levels of glare sensation ('Just Perceptible' and Just 'Noticeable').

The only positive values of the ΔM difference between the means of the variations of the glare index over the test sessions obtained in Day 1 and in Day 2 – signalling a potential influence of learning across the two days – are calculated for the 'Just Perceptible' criterion between the Evening and the Afternoon B sessions (ΔM= 0.85), and for 'Just Noticeable' between the Afternoon B and the Afternoon A sessions (ΔM= 0.77). In both cases, however, after controlling for the effect of the covariate over the independent variable (i.e., assuming fatigue is equal), the inferential statistics show evidence that the difference between Day 1 and Day 2 is not statistically significant and that the effect size is on the borderline of practical relevance (respectively: $F(1,13)= 0.58$, $p= 0.46$, $p\eta^2= 0.04$; and $F(1,13)= 0.64$, $p= 0.44$, $p\eta^2= 0.05$). These results suggest that any significant and practically relevant influence of learning can be excluded from the experimental results previously discussed.

4. Conclusions

The results from this study provide statistically significant evidence that there is a substantive influence of time of the day on the level of glare sensation reported by test subjects within a controlled laboratory experiment. Also from a graphical inspection of the data, Figures 2 to 5 show tendencies that glare sensation votes (GSVs) are reported at higher levels of source luminance as the day progresses. In addition, Figures 6 and 7 confirm that differences in tolerance to luminance appear to be more evident when considering a larger time gap between test sessions. More fundamental questions concerned with why this effect is present were beyond the scope of this investigation.

This study verified that the effect of time of the day on the subjective level of visual discomfort is not likely to be brought on by any influence of learning or experience. Although some evidence of fatigue was present in the findings, the effect of confounding variables was not sufficient to draw any substantial conclusion, therefore requiring additional analysis to uncover the nature of their role. When plots of GSVs were regressed, a large scatter was present in the results, as confirmed by the low coefficient of determination observed using a linear fit (Figures 6 and 7). This is consistent with the literature[1, 2, 3, 4, 24] and suggests that, despite the efforts to control as many variables known to influence glare sensation as possible within the experimental design, there were further factors that appeared to cause individual variations in tolerance to luminance increases. Although it may not be feasible to completely eliminate the scatter commonly associated with subjective evaluation of glare sensation, individual differences may be mitigated if these are systematically identified[9]. Further to this, calculated glare indices were lower than what was expected on a conventional Hopkinson analogue scale. This suggests that participants may have had some difficulty in making informed reports of glare sensation due to the abstract nature of the source and the artificial setting. For future studies, a different measuring criterion will be used, so as to reduce the influence of self-interpretation and guarding the meaning of each glare criterion. On-going research by the authors is also testing the relationship between visual performance and the variation of subjective sensitivity to visual discomfort according to time of the day, and is looking at evaluating the influence of several other temporal and personal variables on individual glare sensation.

Lastly, findings from this study were derived from a laboratory setting, whereby several variables that could potentially influence the glare sensation were controlled or masked from the environment. The hypothesis that a potential effect of time of the day can be detected on the perceived level of discomfort glare from daylight coming from a window remains conjectural and requires further investigation. In this context, future research will look at the influence of temporal diversity on the evaluation of discomfort glare in side-lit occupied spaces (e.g., offices), analysing the possible consideration of time of the day in comfort-based metrics (e.g., the Daylight Glare Probability index[1]), so as to allow a more holistic understanding of daylight performance in buildings.

Conflict of Interest Statement

The authors wish to declare that there is no conflict of interest.

References

1. Wienold J, Christoffersen J. Evaluation methods and development of a new glare prediction model for daylight environments with the use of CCD cameras. *Energy and Buildings* 2006; 38: 743-757.
2. Tregenza P and Wilson M. *Daylighting Architecture and Lighting Design*. London: Routledge, 2011.
3. Tuaycharoen N and Tregenza PR. Discomfort glare from interesting images. *Lighting Research and Technology* 2005; 37 (4): 329-341.

4. Tuaycharoen N and Tregenza PR. View and discomfort glare from windows. *Lighting Research and Technology* 2007; 39 (2): 185-200.
5. Tuaycharoen N. Windows are less glaring when there is a preferred view. *Built - Environment - Sri Lanka* 2011; 09-10 (01-02): 45- 55.
6. Kuhn T, Wienold J and Moosmann C. Daylight glare. Age effects and their impact on glare evaluation: *Proceedings of the Energy Forum: Advanced Buildings Skins.* Bressanone, 2013.
7. Pulpitlova J and Detkova P. Impact of the cultural and social background on the visual perception in living and working perception: *Proceedings of the International Symposium: Design of Amenity*, Fukuoka, 1993.
8. Aries MBC. *Human lighting demands: Healthy lighting in an office environment*. PhD Thesis. Eindhoven: Technische Universiteit Eindhoven, 2005.
9. Rodriguez RG and Pattini A. Tolerance of discomfort glare from a large area source for work on a visual display. *Lighting Research and Technology* 2014; 46 (2): 157-170.
10. Altomonte S. Daylight and the Occupant. Visual and physio-psychological well-being in built environments: *PLEA 2009 - 26th Conference on Passive and Low Energy Architecture*, Quebec City, 2009.
11. Lockley SW. Circadian rhythms: Influence of light in humans. *Encyclopaedia of Neuroscience* 2009; 2: 971-988.
12. Brainard GC, Hanifin JP, Greeson JM, et al. Action spectrum for melatonin regulation in humans: evidence for a novel circadian photoreceptor. *Journal of Neuroscience* 2001; 21 (16): 6405-6412.
13. Osterhaus WKE. Discomfort glare assessment and prevention for daylight applications in office environments. *Solar Energy* 2005; 79: 140-158.
14. Rockcastle S and Andersen M. *Annual Dynamics of Daylight Variability and Contrast. A Simulation-based Approach to Quantifying Visual Effects in Architecture*. London: Springer, 2013.
15. Andersen M, Mardaljevic J and Lockley SW. A framework for predicting the non-visual effects of daylight - Part I: Photobiology-based model. *Lighting Research and Technology* 2012; 44 (1): 37-53.
16. Cajochen C, Zeitzer JM, Czeisler CA, et al. Dose-response relationship for light intensity and ocular and electroencephalographic correlates of human alertness. *Behavioural Brain Research* 2000; 115: 75-83.
17. Zeitzer JM, Dijk DJ, Kronauer RE, et al. Sensitivity of the human circadian pacemaker to nocturnal light: melatonin phase resetting and suppression. *Journal of Physiology* 2000; 526 (3): 695-702.
18. Zeitzer JM, Khalsa SBS, Boivin DB, et al. Temporal dynamics of late-night photic stimulation of the human circadian timing system. *American Journal of Physiology, Regulatory, Integrative and Comparative Physiology* 2005; 289: 839-844.
19. Phipps-Nelson J, Redman JR, Dijk DJ, et al. Daytime exposure to bright light, as compared to dim light, decreases sleepiness and improves psychomotor vigilance performance. *SLEEP* 2003; 26 (6): 695-700.
20. Mardaljevic J, Andersen M, Roy N, et al. *Daylighting, Artificial Lighting and Non-Visual Effects Study for a Residential Building* 2012. Retrieved 30 April 2014, from http://infoscience.epfl.ch/record/181055.

21. Boff KR and Lincoln JE, editors. *User's Guide. Engineering Data Compendium: Human Perception and Performance*. Wright-Patterson Air Force Base, Ohio: Human Engineering Division, 1988.
22. Velds M. *Assessment of lighting quality in office rooms with daylighting systems*. PhD Thesis. Delft: Technische Universiteit Delft, 1999.
23. Hopkinson RG. The multiple criterion technique of subjective appraisal. *Quarterly Journal of Experimental Psychology* 1950; 2 (3): 124-131.
24. Velds M. User acceptance studies to evaluate discomfort glare in daylit rooms. *Solar Energy* 2002; 73 (2): 95-103.
25. Iwata T, Shukuya M and Somekawa N. Experimental study of discomfort glare caused by windows: Subjective responses to glare from simulated windows. *Journal of Architecture, Planning and Environmental Engineering* 1992a; 432: 21-30.
26. Iwata T, Shukuya M, Somekawa N, et al. Experimental study on discomfort glare caused by windows - Subjective response to glare from actual windows. *Journal of Architecture, Planning and Environmental Engineering* 1992b; 439: 19-31.
27. Iwata T and Tokura M. Examination of limitations of predicted glare sensation vote (PGSV) as a glare source - Towards a comprehensive development of discomfort glare evaluation. *Lighting Research and Technology* 1998; 30: 81-88.
28. Mochizuki E, Itoh D and Iwata T. Effects on discomfort glare of luminance distribution with a window. *J. Environ. Eng., AIJ* 2009; 74 (637): 277-282.
29. CIBSE, *Code for Interior Lighting*, London: CIBSE, 1994.
30. CIE, *Discomfort Glare in Interior Lighting*, CIE Technical Report117, Vienna: CIE, 1995.
31. SLL, *The SLL Code for Lighting*, London: CIBSE, 2012.
32. Heiman GW. *Basic Statistics for the Behavioural Sciences 7thEdition*. Stamford: Cengage, 2013.
33. Field A. *Discovering Statistics Using IBM SPSS Statistics*. 4th Edition. London: Sage, 2013.
34. Ellis PD. *The Essential Guide to Effect Sizes: Statistic Power, Meta-Analysis, and the Interpretation of Research Results*. Cambridge: Cambridge University Press, 2010.
35. Cohen J. *Some statistical issues in psychological research*. In Wolman BB, editor. Handbook of clinical psychology. New York: McGraw-Hill; 1965.
36. Schiavon S and Altomonte S. Influence of factors unrelated to environmental quality on occupant satisfaction in LEED and non-LEED certified buildings. *Building and Environment* 2014; 77: 148-159.
37. Ferguson CJ. An effect size primer: a guide for clinicians and researchers. *Professional Psychology: Research and Practise* 2009; 40 (5): 532-538.
38. Siegel S. Nonparametric statistics. *The American Statistician* 1957; 11 (3): 13-19.