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Discomfort glare evaluation: The influence of anchor bias in luminance adjustments

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Luminance adjustment is a procedure commonly used to evaluate discomfort glare and the results from adjustment experiments form the basis of some recommendations for limiting its occurrence. There are, however, strong reasons to expect that settings made using adjustment are unintentionally influenced by extraneous variables. This paper discusses bias towards the initial anchor, the setting of the variable stimulus immediately before an adjustment is made. Specifically, the initial luminance is expected to influence the setting that is made by adjustment; for example, a lower initial luminance leads to a lower setting than a high initial luminance. To investigate anchor bias, a Hopkinson-like multiple-criterion adjustment experiment was undertaken, but with three different anchors. The results confirmed significant bias: glare settings were biased towards the luminance of the initial anchor. This demonstrates a need for caution when using adjustment to explore discomfort glare and when interpreting the results of past studies that used discomfort glare models fitted to data obtained with this procedure.

1. Introduction

1.1. Models of discomfort glare

Discomfort glare is generally defined as a psychological sensation that causes distraction or annoyance without necessarily being linked to a reduction in visual ability.[1,2] This discomfort arises from the luminance of a light source (or luminance contrast) within the visual field of an observer that is sufficiently greater than the conditions to which the eyes are able to adapt to.[3]

Lighting designers aim to minimise the risk of causing discomfort[3,4] and one means for doing this is to calculate, for a proposed lighting installation, one of a number of recommended glare indices. Among such indices is the Unified Glare Rating (UGR),[5] shown in equation (1), as recommended by the Society of Light and Lighting (SLL)[4] and originally developed by the International Commission on Illumination (CIE).[5] The UGR describes the level of discomfort due to glare according to the luminance, size, and location of the light source, and the luminance of the background

$$\text{UGR} = 8 \log \frac{0.25}{L_b} \sum_{i=1}^{n} \left(\frac{L_s^2 \cdot \omega_s}{P_s^2} \right) \qquad (1)$$

where L_s = source luminance (cd/m^2), ω_s = subtended solid angle of the glare source (sr), L_b = background luminance (cd/m^2), P = Guth's position index (–).

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The UGR is a development of the Illuminating Engineering Society Glare Index (IES-GI),[6] but with an alternative approach to account for the luminance of the background.[7,8] The IES-GI (equation (2)) is itself a development of the Glare Constant (equation (3)) established in the discomfort glare studies of Petherbridge and Hopkinson,[9] but with a logarithmic function to account for the sensitivity of the visual system[10]

$$IES - GI = 10\log_{10} \cdot (\text{Glare Constant}) \quad (2)$$

$$\text{Glare Constant (g)} = \frac{L_s^{1.6} \cdot \omega^{0.8}}{L_b \cdot P^{1.6}} \quad (3)$$

The UGR and CIE discomfort glare systems were derived from the IES-GI without further experimental evaluations of discomfort glare sensation. In fact, during the development of the UGR, Sorensen[8] stated that the '*basic formula* [IES-GI] *appears [. . .] to be sound and the glare index concept is well established in the countries for which this method was developed. The basic formula was, therefore, accepted as the "dogmatic truth"*'.

In other words, the discomfort glare model currently recommended by SLL[4] can be traced back to the glare experiments carried out by Petherbridge and Hopkinson.[9] As a matter of fact, the basic form of the IES-GI is still utilised in modern glare formulae (e.g. UGR).

To establish the Glare Constant on which the IES-GI is based, Petherbridge and Hopkinson[9] carried out a series of experiments in which test participants were asked to observe the interior of a scaled model of a room. Apertures were cut into a screen covering the far wall, behind which was a source of light. This provided background lighting for the room, which was also lit by independent light sources. Observers adjusted the brightness of this background lighting, varying the contrast between the apparent light sources and the background, until each of four predefined criteria of discomfort glare sensation were reached: Just Imperceptible, Just Acceptable, Just Uncomfortable and Just Intolerable (Table 1). This is the process Petherbridge and Hopkinson named the 'multiple criterion technique'.

Although glare indices are intended to provide consistent predictions across a range of conditions and measurement methods, many studies have reported large inconsistencies between subjective evaluations of discomfort glare sensation and the IES-GI.[11–18] For example, previous work by the authors has shown extremely wide variance when values of IES-GI calculated from adjustments made to the source luminance were plotted against the level of glare sensation provided by test subjects[13] (Figure 1).

While discomfort glare is widely discussed in research and lighting design practice, it is not yet fully understood.[19–21] One factor that may be limiting progress towards its better characterisation is an insufficient

Table 1 Definitions of the four criteria of discomfort glare sensation[9]

| Glare criteria		Definition
A	Just Intolerable	The changeover point between intolerable and uncomfortable
B	Just Uncomfortable	The changeover point between uncomfortable and merely distracting glare
C	Just Acceptable	The changeover point between distracting and acceptable glare
D	Just Imperceptible	The changeover point where glare from the sources is just no longer noticeable; the sources themselves are still noticeable, but they merge into the general field of view in such a way that they no longer form any source of attraction
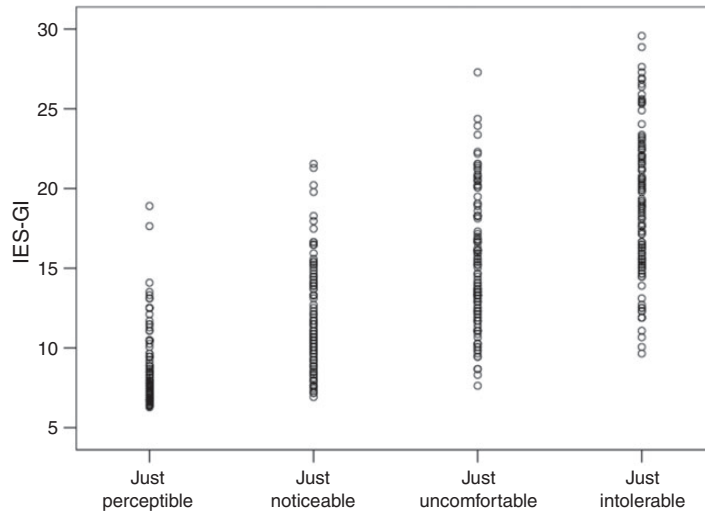
Figure 1 Glare sensation votes against calculated values of IES-GI[13]

consideration of experimental methodologies. In this paper, we explore the contribution to the variance that might be attributed to one part of the adjustment procedure employed by Petherbridge and Hopkinson.

1.2. Adjustments and heuristic anchoring

When using the adjustment task in glare experiments, either the glare source or its background can be varied. Hopkinson[22] suggested that observers often felt more confident when the source luminance was held constant and were instructed to adjust the luminance of the background. For this reason, Petherbridge and Hopkinson,[9] and other studies by Hopkinson,[23–26] mostly used adjustment of background luminance to the four predefined discomfort glare criteria, while adjustment of the source luminance was seldom utilised.[27] Adjustments to the four predefined discomfort criteria presented in Table 1 were consistently made in order of increasing magnitude. This is stated explicitly in Hopkinson and Bradley[27]:

> *To begin, the source was off* ... [the observer] *had previously been explained what was demanded of him, first, to raise the brightness of the source himself by means of the dimming control knob until the threshold of glare (Criterion D) was reached... the observer then slowly raised the brightness of the source again, allowing pauses for adaption, until the next degree, just acceptable glare (Criterion C) was reached. Criterion (B) just uncomfortable glare came next, and finally criterion A, just intolerable glare*

When participants use an adjustment procedure to make judgements of a variable stimulus, it has been proposed that the final setting is influenced by the initial stimulus.[28] This phenomenon is known as anchoring.[29] Anchors can affect a large range of judgements, including responses to general knowledge questions, economic evaluations, and social values.[30,31] When making a quantitative subjective assessment, different starting points lead to different values, which tend to be biased towards the initial settings.[29,32] In other words, judgements of a variable stimulus might be substantially lower if a low rather than a high anchor is given to start

with.[33]Anchoring has been demonstrated also in lighting studies.

To confirm that, when an adjustment procedure was used, the reported mean luminance could be explained by stimulus range bias (i.e. the mean luminance was located at the centre of the range of available luminance variation).[34–36] Fotios and Cheal[37] carried out an experiment to investigate preferred light levels. Twenty-one participants were instructed to adjust the brightness inside a small booth until they achieved '*satisfaction with the light level*'. The trial was repeated using three ranges of illuminance (48–1037 lux; 83–1950 lux; 165–2550 lux) without the observer being informed of the change. These three ranges led to significantly different settings.

In their experiment,[37] both low and high anchors were used, these being the minima and maxima of each of the three ranges, and it was found that mean-adjusted illuminances were consistently biased towards the initial setting. One limitation of the procedure, however, is that the sequence of high and low anchors was not randomised but the low anchor was always experienced first. The anchoring effect was therefore further investigated in two studies seeking settings of preferred light level[38,39] and in one study seeking settings of preferred correlated colour temperature[40]: significant anchoring effects were found in all cases.

A study by Osterhaus and Bailey[41] also provides evidence of anchoring bias in the evaluation of discomfort glare. Observers adjusted the luminance of a large field surrounding a monitor screen (maintained at 12.5 cd/m^2) to identify two glare thresholds. These settings were made to six different initial luminances, ranging from 6.3 to 2000 cd/m^2. The results showed that the adjustments were influenced by the initial setting: '*subjects selected higher luminances when high initial presentation luminances preceded the adjustment*'. Moreover, Stone and Harker[16] included conditions that would allow analysis of the effect of anchoring in a glare adjustment trial, but did not report any results that would permit such analysis.

The adjustment procedure presents a variable stimulus that is controlled by test subjects to identify a threshold value (or their preferred setting). According to the literature,[42] on successive trials, the variable stimulus should be set initially to values far above and far below the expected threshold value, and then the absolute value should be taken as the mean of these two settings. Boyce *et al.*[43] used an alternative approach to investigate preferred light levels, since their dimming control was set initially to the 50% position. Logadóttir *et al.*[38] examined this by using a mid-range anchor in addition to low and high initial settings. While they found that the preferred illuminances using only the middle anchor were significantly higher than the mean of the low and high anchors, they also noted that the non-linear response of their dimming controller may have influenced this disagreement.

In summary, the literature provides reasons to believe that adjustment tasks traditionally used in glare experiments might be biased towards the initial luminance setting. If this proves correct, the results from the Petherbridge and Hopkinson[9] study – and, hence, the resulting IES-GI index – might provide an incorrect estimate of the background light level (or, more precisely, the relationship between background and target luminances) associated with each glare criterion. To test this hypothesis, an experiment was carried out to confirm whether the initial luminance settings of a variable stimulus (anchor) affect the luminance associated with a given magnitude of discomfort glare.

2. Method

2.1. Experimental setup

Discomfort from artificial lighting was evaluated in laboratory tests, using a
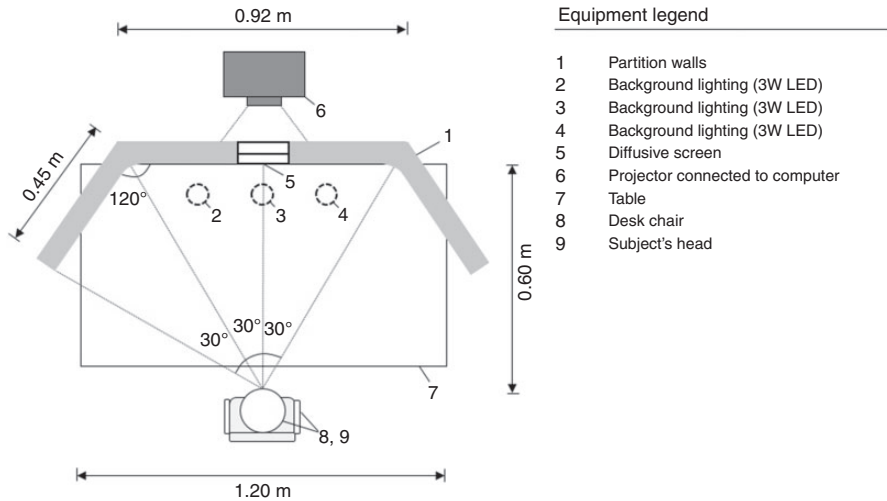
Figure 2 Plan of the testing apparatus

procedure designed to explore whether anchoring effects (i.e. resulting from different initial settings of source luminance) could be detected. For this study, the background luminance, the subtended area of the glare source, and the position of the glare source in the field of vision of the observer were held constant. There were no extraneous sources of natural or artificial light within the testing apparatus and all other extraneous variables (i.e. temperature, humidity and background noise level) were measured before and after each test session.

The design of the testing apparatus (Figure 2) was informed by previous studies[11,13,14,17] that investigated the influence of time of day and view interest on the subjective evaluation of glare sensation.

The testing chamber was semi-hexagonal in plan. The interior surfaces (2.7 m in height) were painted matte white, and three 3 W LED lamps were mounted above the subject's head position to produce background lighting with a constant luminance distribution. Luminances were measured from the location of the participant using a Minolta LS-100 luminance meter mounted on a tripod. From this position, the mean background luminance was calculated from 17 individual measurements taken on a regular grid symmetrical about the central fixation point and extended across the width of the apparatus.[13,14,17] The mean luminance was held constant at 65 cd/m^2 throughout the experimental procedure, since this value is within the range commonly found in interior spaces.[44] The background luminance was measured before and after each test session. The corners where the partition walls met at 120° angles were covered with matte-white tape to increase light uniformity across the chamber.

A desk with a diffusive white surface was mounted within the wooden partitions. The subject's head position was set at a height of 1.2 m from the floor, facing a small diffusive screen (0.08 m × 0.04 m) made from three sheets of translucent paper and mounted in front of a projector connected to a computer. The paper had uniform transmission properties allowing direct light from the projector to be evenly diffused across the area of the small screen. According to the literature, glare indices for artificial lighting are designed to

deal with small sources subtending a solid angle below 0.01 steradians.[45,46] For this reason, the small diffusive screen subtended an angle at the eye of 0.009 steradians and provided a variable luminance in the range between 200 and 32,000 cd/m². The luminance of the small diffusive screen was measured using a series of spot-point measurements. The source luminance was progressively increased using the relative brightness function of an image editing software, which was operated by the experimenter. In order to achieve precise luminance values in repeated procedures, the projector had to be calibrated. To do this, the relative brightness was increased at evenly adjusted intervals and spot-point measurements were taken at each interval. Luminance values at each interval were then plotted on a curve using a polynomial function to obtain values between calibrated luminance points.

2.2. Experimental procedure

To test the hypothesis that different initial source luminances lead to different adjustments for the same level of reported glare sensation, participants were asked to provide glare judgements under three initial settings corresponding to a low, medium, and high anchor.[38] Since no established luminance value could be utilised to specify these anchors, the discomfort glare criteria for the IES-GI were used (Table 2).[10,26] These were

calculated according to the following formula (equation (4), based on equations (2) and (3))

$$IES - GI = 10\log_{10} \cdot 0.478 \sum_{i=1}^{n} \frac{L_s^{1.6} \cdot \omega_s^{0.8}}{L_b \cdot P_s^{1.6}}$$

(4)

For each anchor, the luminance of the diffusive screen was set to an initial brightness (Table 2) corresponding to an IES-GI that, on the Hopkinson scale, describes the source as being, respectively: Just Imperceptible (low anchor); borderline between comfort and discomfort or BCD (medium anchor); and Just Uncomfortable (high anchor). On Hopkinson's scale, the BCD lies between criterion B and criterion C.[26] The Just Uncomfortable criterion was used for the high anchor to avoid any potential harm to the participants with an initial setting corresponding to a glare index of Just Intolerable.

During the experimental procedure, test participants were asked to make judgements of visual discomfort using the glare criteria and descriptors used in the development of the Glare Constant[9] and the IES-GI[6,10] (Table 1). Since it was considered that each descriptor could be open to self-interpretation due to the abstraction caused by the assessment, to aid subjects giving more meaningful judgements each criterion was linked to Hopkinson's detailed protocol published in MacGowan[47] and to time-span descriptors[45] (see Appendix 1).

Participants were first asked to adjust the chair so that their head was located at the correct viewing height. A set of instructions was then given including a definition of discomfort glare, the meaning of the four glare criteria, and a description of the procedure. To reinforce the participants' understanding of the four glare criteria, a pre-test condition was provided. The diffusive screen was set to one of the initial luminance settings, chosen at random. Participants

Table 2 Definition of the three anchors according to the IES-GI and discomfort glare criteria

Anchor	Source luminance (cd/m²)	IES-GI	Discomfort glare criteria
Low	1627	10	Just Imperceptible
Medium	5414	18.5	BCD
High	8999	22	Just Uncomfortable

BCD: borderline between comfort and discomfort; IES-GI: Illuminating Engineering Society Glare Index.

were asked whether they would like the experimenter to increase, decrease or keep constant the brightness of the screen and to indicate when the brightness of the screen first reached a sensation of Just Imperceptible glare. For each trial, the experimenter adjusted the luminance of the diffusive screen at a controlled pace according to the participant's instruction. Once the lowest of the four criteria had been met, the luminance of the screen was increased and subjects were instructed to indicate when the other glare criteria were reached in order of increasing discomfort. The pre-test condition was followed by a pause of two minutes.

The brightness of the diffusive screen was then set to a specific initial source luminance anchor, chosen at random, and participants were asked to make the first of a series of recorded glare evaluations. Following the procedure adopted by Hopkinson and Bradley,[27] the subject was asked to direct their gaze towards the centre of the diffusive screen and to vocally indicate when its brightness reached, respectively, a sensation of Just Imperceptible, Just Acceptable, Just Uncomfortable, and Just Intolerable glare. Once each criterion was reached, the screen luminance was recorded. It must be noted that, for this experiment, the four levels of discomfort glare were always evaluated in order of increasing magnitude so as to follow closely the original procedure used by Hopkinson.[9] However, as already indicated by Pulpitlova and Detkova,[48] it is likely that this sequence might influence the adjustments made.

The IES-GI was calculated from the recorded luminances. After making the initial four evaluations, participants were given a short relaxation period (two minutes) before continuing the experiment starting with the next luminance anchor. The test procedure was again repeated until the subject had provided all four levels of glare sensation under each of the three different luminance anchors. To help mask any unwanted procedural effects (e.g. learning, fatigue), the luminance anchors were presented to each test participant in a randomised sequence.[49] Each test session lasted approximately 30 minutes.

Twenty-two subjects volunteered to participate in this experiment. They were recruited via an online advertisement addressed to all postgraduate students in the Department of Architecture at the University of Nottingham. The sample comprised 8 males and 14 females, with a mean age of 29.6 years (SD = 3.75 years). Seventeen subjects wore their normal glasses or corrective lenses, and all self-certified as having no other health or eye problems.

3. Results

3.1. Adjustment task and initial luminance settings

Table 3 presents the mean source luminances of the diffusive screen and their associated standard deviation at the point in which participants reported each criteria of glare sensation for each of the three anchors. Initial inspection of the data shows that

Table 3 Mean source luminance (and standard deviation) for the three anchors and the four glare criteria

Anchor	Mean luminance (cd/m²)			
	Just Imperceptible	Just Acceptable	Just Uncomfortable	Just Intolerable
Low	1784 (1031)	3043 (1534)	4517 (2027)	8238 (4135)
Medium	3192 (1341)	4350 (1982)	5858 (1982)	10 130 (3388)
High	5663 (2923)	7224 (3037)	9031 (3232)	13 548 (4858)

values of mean source luminance increase when considering a higher anchor for each level of glare sensation. This suggests that participants made adjustments to each of the predefined glare criteria closer to the luminance of the initial setting. However, since source luminance alone is not a reliable indicator of discomfort glare,[46] results were analysed utilising the IES-GI formula.

Figure 3 presents, on the x-axis, the four glare criteria provided by the test subjects according to the three initial luminance anchors. On the y-axis, the figure plots, on the left side, the mean IES-GI values of the small diffusive screen. On the right side, the figure presents the interpretation of the IES-GI derived from Hopkinson,[10] where benchmarks are provided for Just Imperceptible, Just Acceptable, BCD, Just Uncomfortable, and Just Intolerable glare (IES-GI $\geq$ 10, 16, 18.5, 22, 28, respectively). Calculated values

of IES-GI below 10 are denoted as the condition that would not cause any glare sensation.

Figure 3 reveals a tendency for the IES-GI to be influenced by the luminance anchors. Specifically, mean values of IES-GI are consistently biased towards the initial luminance setting for each level of reported glare sensation, such that for each glare criterion the low anchor leads to a lower value of IES-GI and the high anchor leads to a higher value of IES-GI. This trend is apparent for all glare criteria. This confirms the experimental hypothesis that, when adjustment tasks are used, glare settings are made closer to the luminance of the anchor. For each glare criterion, the differences in mean IES-GI across the three initial luminance settings also appear to decrease when considering a higher level of visual discomfort. In this context, it should be remembered that
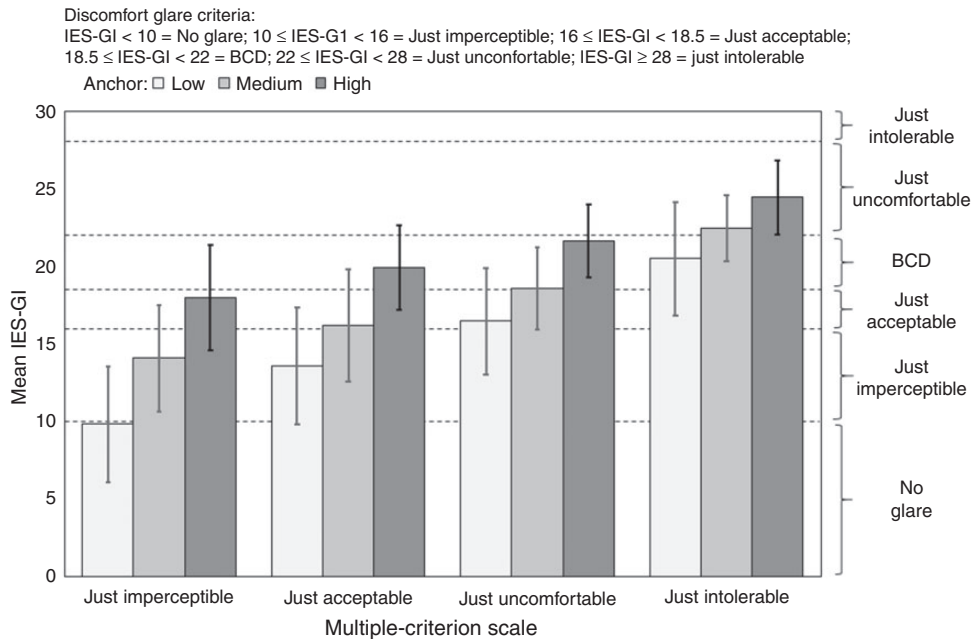

Figure 3 Mean IES-GI for the three luminance anchors and the four glare criteria (error bars show the standard deviation)
BCD: borderline between comfort and discomfort.

participants were initially instructed to make judgements of glare sensation to the lowest glare criterion (Just Imperceptible), and then to the others in order of increasing visual discomfort.

Null hypothesis significance testing (NHST) was performed to determine if the differences between independent groups were significantly different. However, since NHST is dependent on both the size of the sample and on the magnitude of the effect under examination,[50] emphasis of the analysis was placed on the effect size (i.e. a standardised measure of the observed difference across the independent variable)[51,52] and not only on the statistical significance (which, in cases of small or uneven samples, could confound the outcome).[53–55]

To analyse the data, a repeated-measures Analysis of Variance (RM-ANOVA) was initially run to compare the glare indices for each level of glare sensation across the three different anchors. This test was selected since graphical (Q–Q plot) and statistical (Shapiro–Wilk and Kolmogorov–Smirnov tests) inspection of the data revealed normal distributions around the mean (statistical results are not provided here). The Maulchly's test of sphericity was also used to test whether the variances of the differences between all paired comparisons of the within-subject variable were equal.[56,57] The test revealed that the differences in variance across the independent groups, and for each glare criterion, were not statistically significantly different: Just Imperceptible: $\chi^2(2) = 3.63$, $p = 0.16$ n.s.; Just Acceptable: $\chi^2(2) = 1.56$, $p = 0.46$ n.s.; Just Uncomfortable: $\chi^2(2) = 3.93$, $p = 0.14$ n.s.; Just Intolerable: $\chi^2(2) = 3.83$, $p = 0.15$ n.s. Since the assumptions of normality and of sphericity were not violated, parametric tests were suitable for this analysis.[58]

Table 4 presents the results of the RM-ANOVA, providing the glare levels on the multiple criterion scale, the test statistic (F)

Table 4 RM-ANOVA (sphericity assumed)

Multiple-criterion scale	$F(2,42)$	Statistical significance (*p*-value)	Effect size ($p\eta^2$)
Just Imperceptible	50.54	$p \leq 0.001$	0.71
Just Acceptable	34.95	$p \leq 0.001$	0.63
Just Uncomfortable	33.00	$p \leq 0.001$	0.61
Just Intolerable	24.86	$p \leq 0.001$	0.54

$p\eta^2 < 0.04 =$ negligible; $0.04 \leq p\eta^2 < 0.25 =$ small; $0.25 \leq p\eta^2 < 0.64 =$ moderate; $p\eta^2 \geq 0.64 =$ large. RM-ANOVA: repeated-measures Analysis of Variance.

and the degrees of freedom, the statistical significance (*p*-value), and the effect size ($p\eta^2$). The interpretation of the outcome was derived from Ferguson,[59] where benchmarks are given for small, moderate, and large effect sizes ($p\eta^2 \geq 0.04$, 0.25, and 0.64, respectively). Values of $p\eta^2$ below 0.04 denote not substantive (i.e. not practically relevant) influences.

The results from the RM-ANOVA demonstrate that the differences in mean values of calculated IES-GI across the three anchors for all glare criteria are highly significant. The differences detected all have substantive effect sizes, ranging between large ($p\eta^2 = 0.71$ for 'Just Imperceptible') and moderate ($0.25 \leq p\eta^2 < 0.64$ for all other glare criteria). Interestingly, when participants reported high levels of glare, the magnitude of effect size decreases. This indicates that the differences in mean IES-GI across the three anchors become smaller, hence confirming what had previously been noted from graphical inspection of the data (Figure 3).

Post hoc testing was then performed, whereby all combinations between the initial luminance settings were compared against each other, and the statistical significance of the differences was calculated using one-tailed paired t-tests to determine where the variations detected in the RM-ANOVA were. Directionality of the hypothesis was informed by inspection of the central tendencies and graphical displays of the data.[60] Since

Table 5 Paired comparison t-tests and effect sizes

Multiple-criterion scale	Anchors	M (SD)	M (SD)	ΔM^{NHST}	CI_L, CI_U	Effect size (d)
Just Imperceptible	Low vs Medium	9.81 (3.74)	14.07 (3.43)	−4.26***	−6.53, −1.98	−1.18
	Low vs High	9.81 (3.74)	17.97 (3.40)	−8.16***	−10.51, −5.80	−2.28
	Medium vs High	14.07 (3.43)	17.97 (3.40)	−3.90***	−5.53, −2.27	−1.14
Just Acceptable	Low vs Medium	13.57 (3.78)	16.17 (3.58)	−2.60**	−4.81, −0.40	−0.71
	Low vs High	13.57 (3.78)	19.92 (2.73)	−6.35***	−8.43, −4.36	−1.93
	Medium vs High	16.17 (3.58)	19.92 (2.73)	−3.75***	−5.48, −2.02	−1.18
Just Uncomfortable	Low vs Medium	16.45 (3.44)	18.55 (2.66)	−2.10*	−4.00, −0.21	−0.68
	Low vs High	16.45 (3.44)	21.61 (2.36)	−5.16***	−6.91, −3.41	−1.75
	Medium vs High	18.55 (2.66)	21.61 (2.36)	−3.06***	−4.34, −1.78	−1.22
Just Intolerable	Low vs Medium	20.47 (3.67)	22.47 (2.13)	−2.00**	−3.54, −0.47	−0.67
	Low vs High	20.47 (3.67)	24.42 (2.40)	−3.95***	−5.60, −2.29	−1.27
	Medium vs High	22.47 (2.13)	24.42 (2.40)	−1.94***	−3.07, −0.82	−0.86

With Bonferroni corrections: *weakly significant; **significant; ***highly significant.
d < 0.41 = negligible; 0.41 ≤ d < 1.15 = small; 1.15 ≤ d < 2.70 = moderate; d ≥ 2.70 = large.
NHST: null hypothesis significance testing; n.s.: not significant.

there was convincing evidence of a direct relationship between initial anchors and calculated mean IES-GI for each glare criterion, a one-tailed hypothesis was applied.[61] In consideration of the experiment-wise error rate caused by the alpha level inflating across multiple pairwise comparisons – which was calculated as $1 – (0.95)^n = 0.14$ (thus, risking a 14% probability of making at least one Type I error), whereby n = 3, i.e. the number of tests carried out on the same data and with the same hypothesis[62] – Bonferroni corrections were applied.[58] In this analysis, the effect size was calculated by the Cohen's d coefficient, according to equation (5)[63]

$$\text{Cohen's d} = \frac{M_1 - M_2}{\sigma_{Pooled}} \qquad (5)$$

where M_1 and M_2 are the mean values across the paired comparison and σ_{Pooled} is the pooled standard deviation.

The interpretation of the outcome was derived from the benchmarks provided by Ferguson[59] for small, moderate, and large effect sizes (d ≥ 0.41, 1.15, and 2.70, respectively). Values below 0.41 were not considered to be substantive influences (i.e. they were not deemed as practically relevant effects).

Table 5 reports the results of the t-tests, providing, for each glare criterion, the comparison under examination (anchors), the mean and standard deviations for the calculated IES-GI (M and SD), the mean differences (ΔM), their statistical significance (NHST), and their 95% upper (CI_U) and lower (CI_L) confidence intervals, and the effect size (d).

Inspection of the descriptive and inferential statistics shows that the sign of the mean differences and of the effect sizes are consistently negative across all comparisons, therefore signalling higher values of IES-GI when participants adjusted the luminance of the glare source starting from a higher initial anchor. The differences in means are highly significant in 9 cases, significant in 2 cases, and weakly significant in 1 out of 12 cases. All differences have a substantive effect size ranging from moderate (Cohen's d absolute value 1.15 ≤ d < 2.70 in seven cases) to small (0.41 ≤ d < 1.15 in five cases).

Statistical analysis of the data hence confirms that, when the initial anchor of the stimulus was increased, test subjects made adjustments to higher luminance settings for the same level of reported glare sensation. The effect of the anchor on the glare settings

made by participants also appeared to be larger when considering a bigger difference in the luminance of the initial anchor. In fact, comparisons between the 'low' and 'high' anchors produced the largest differences in mean IES-GI and effect size for every glare criterion.

The findings also show that, when considering higher levels of visual discomfort, the differences in mean (ΔM) and the effect sizes reduce across comparisons. This suggests that the effect of the initial anchor on adjustments to the subjective glare criteria decreases when participants reported higher glare sensation. However, this might have occurred since participants were instructed to make adjustments to the four criteria on Hopkinson's multiple-criterion scale using only a sequence of increasing glare evaluation, i.e. starting from the lowest (Just Imperceptible) to the highest level of visual discomfort. Conversely, the procedure for this experiment did not consider how adjustments to the four predefined criteria could have influenced the outcome of the study if other orders had been used.

4. Discussion

Table 6 displays, for each level of glare sensation provided by test participants, the anchor, the mean calculated IES-GI and, in parenthesis, the corresponding glare criterion based on Hopkinson's scale.[10] The results show that, for the same level of glare sensation reported across the three initial anchors, the mean values of IES-GI correspond to different discomfort glare criteria. For example, for the Just Imperceptible criterion reported by subjects (left column), the mean calculated values of IES-GI for the low, medium, and high anchors correspond, respectively, to the Hopkinson's discomfort glare criteria of: No Glare, Jus Imperceptible, and Just Acceptable. This demonstrates that, when adjustment

Table 6 Initial luminance setting and corresponding discomfort glare criteria

Multiple-criterion scale	Anchor	Mean IES-GI (discomfort glare criteria)
Just Imperceptible	Low	9.81 (No glare)
	Medium	14.07 (Just Imperceptible)
	High	17.97 (Just Acceptable)
Just Acceptable	Low	13.57 (Just Imperceptible)
	Medium	16.17 (Just Acceptable)
	High	19.92 (BCD)
Just Uncomfortable	Low	16.45 (Just Acceptable)
	Medium	18.55 (BCD)
	High	21.61 (BCD)
Just Intolerable	Low	20.47 (BCD)
	Medium	22.47 (Just Uncomfortable)
	High	24.42 (Just Uncomfortable)

BCD: borderline between comfort and discomfort; IES-GI: Illuminating Engineering Society Glare Index.

tasks are performed from different initial luminance levels, the final estimates vary considerably when levels of IES-GI are used to describe the subjective evaluation of glare sensation. This might also question the alleged precision of the glare index values from bright light sources calculated to estimate or predict the levels of visual discomfort inside buildings.

Regardless of the anchor used in the current work, the mean IES-GI values presented in Table 6 are consistently lower than the standard discomfort glare criteria corresponding to Just Uncomfortable and Just Intolerable (i.e. IES-GI < 22 and 28, respectively) for the same reported level of glare sensation. Similar inconsistencies were reported by Akashi *et al.*,[64] who found that UGR values overestimated glare ratings given under several fixed conditions. Although it is difficult to determine the exact reasons behind these inconsistencies, in part because different experimental procedures were used, it is likely that glare evaluations were influenced by the available range of the variable stimulus (i.e. range bias). In the current work, the maximum luminance was 32,000 cd/m^2: if a lower or higher maximum luminance had been used,

Table 7 Comparison of BCD settings

Data	Source size (sr)	Distance from source (m)	Luminance background (cd/m^2)	Adjusted source luminance (cd/m^2)	IES-GI
Luckiesh and Guth[68]	0.001	1.02	34	3053	10.64
Low anchor	0.009	0.60	65	3781	15.19
Medium anchor	0.009	0.60	65	5105	17.51
High anchor	0.009	0.60	65	8128	20.83

IES-GI: Illuminating Engineering Society Glare Index.

the results of previous work show that this would have resulted in different settings.[65]

An alternative to the multiple criterion approach is to make adjustments to the BCD, as was done by Guth.[66,67] Table 7 compares settings made to the BCD from the study by Luckiesh and Guth[68] (who had originally proposed the BCD criterion) with the findings from this study. Table 7 displays the source size, the observers distance from the source, background luminance, the source luminance at the point in which observers declared the BCD, and the calculated IES-GI according to equation (4). Although the criterion of BCD does not appear on the multiple-criterion scale, Hopkinson[26] previously had suggested that it belongs between Just Acceptable and Just Uncomfortable, i.e. between the second and third intervals of the four-point scale. Therefore, at each of the three anchors, average values of the settings at which test participants reported Just Acceptable and Just Uncomfortable glare sensation were taken and mean values of IES-GI were calculated. As expected, the adjusted source luminance at the assumed criterion of BCD increases when considering a higher initial anchor. Although the variable stimulus could be adjusted to a much greater range in Luckiesh and Guth's study ([0 cd/m^2 to 102,788 cd/m^2]), the mean IES-GI value is smaller.

Hopkinson's suggestion that BCD lies between the second and third intervals is not however universally accepted; Adrian and Schreuder[69] assumed instead that it was the second interval on the four-point scale, and

such differences in interpretation lead, from the same data, to different estimates of the BCD luminance.

5. Conclusions

The results from this study provide statistically significant and substantive evidence that, in a controlled laboratory experiment, adjustment tasks used to test the degrees of glare sensation from a bright light source are biased by the initial luminance setting (anchor). This confirms the hypothesis derived from a review of the literature on lighting preferences. This study found significant differences in the mean values of calculated glare index across different anchors for equal levels of glare sensation provided by participants. Such mean values were consistently biased towards the initial luminance setting presented to the participants before they were instructed to make adjustments to the glare source.

These results suggest the need to critically review the findings drawn from glare studies that have used adjustments from only a low initial luminance setting. For example, in the experiments by Petherbridge and Hopkinson,[9] observers were consistently instructed to adjust the glare source from a low initial luminance setting, this potentially bringing a bias to the conclusions due to an anchoring effect. Considering that the Petherbridge and Hopkinson study has been used as a fundamental reference for the development of most following glare models,

this also raises some important questions related to the alleged precision of the glare indexes generally used to describe the levels of discomfort due to luminous sources.

In interpreting the results of our experiment, and planning future work, some methodological constraints should be acknowledged. Among these, participants often expressed a difficulty when making judgements of glare sensation for the lowest levels on the multiple-criterion scale, i.e. Just Imperceptible and Just Acceptable glare. In some cases, subjects also reported difficulty in making glare evaluations when directly observing the light source. Lastly, this experiment considered a forward-only order in the adjustments to the four glare criteria, and for future experiments we suggest the adoption of a randomised sequence. These caveats are being addressed in the ongoing experimental work.

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Appendix 1. Definitions of discomfort thresholds as given to test participants

In this experiment, you will be asked to express your own perceived level of discomfort glare when presented to a small diffusive screen, using four threshold criteria of glare sensation votes: 'Just Imperceptible', 'Just Acceptable', 'Just Uncomfortable', and 'Just Intolerable'.

These are described below:

- *Just Imperceptible*: When the source of the light becomes quite bright without necessarily giving a sensation of glare. As the light source is being adjusted, for a moment while performing the visual task, the source would be something that attracts your attention.
- *Just Acceptable*: This corresponds to a glare sensation that could be tolerated for approximately one day when working in this room. If you had to work under this lighting condition at your own workstation, you may want to use blinds or other measures to decrease the perceived discomfort.
- *Just Uncomfortable*: This corresponds to a glare sensation that could be tolerated for approximately 15–30 minutes, for example if finishing a certain task would take this amount of time. After this, adjustments to the lighting conditions would be made, if the same degree of discomfort would be present over time.
- *Just Intolerable*: This corresponds to the point where you would no longer be able to work under these lighting conditions for any amount of time and would immediately intervene to change them.