The Position Index of Overhead LED Sources Under Different Spectral Power Distributions and Background Luminances

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Abstract

The position index was developed by Luckiesh and Guth in 1949 and is widely used in discomfort glare models to account for the position of the glare source when predicting the presence and magnitude of visual discomfort. The applicability of this index to modern LED sources has not been evaluated; however, it is of concern due to potentially higher luminance levels of LEDs compared to the sources used by Luckiesh and Guth. Furthermore, the position index of overhead sources beyond 60° above the line of sight has not been quantified.

An experiment was conducted using a hemispherical apparatus with LED sources. The position of the light source, background luminance, the spectral power distribution, and anchor (starting luminance level before adjustment) were varied and two procedures were used to determine the position index of these sources. Data from 29 participants indicates that overhead sources located 60° or 80° above the line of sight were detectable and their position index can be quantified. The position index values were found to be higher than those reported in previous studies, suggesting that anchor bias and the small luminance range in previous studies likely influenced their position index values. No differences were found in position index values by spectral power distribution, background luminance, participant age group, or eyeglass wearing. The position index values reported in this study account for range and anchor bias, providing a better estimate that should be incorporated into discomfort glare models.

Keywords: position index, discomfort glare, overhead glare

1. Introduction

Discomfort from glare, defined as the sensation of discomfort without impairing the visibility of objects (Commission Internationale de l’Éclairage 2020), can affect the experience of building occupants and pedestrians in lighted outdoor nighttime environments (Commission Internationale de l’Éclairage 2021). Discomfort glare is distinct from disability glare, which by definition does impair visibility, but both types of glare can occur simultaneously. Several models have been proposed to predict the presence and magnitude of discomfort glare in various applications (Hopkinson 1940; Commission Internationale de l’Éclairage 1995; Clear 2012; Rodriguez *et al.* 2017; Abboushi *et al.* 2023). Often, these equations take into account the luminance and size of the glare source, the background luminance (either as a way to express the contrast of the source against its background, or as a proxy for the observer adaptation luminance), and a term representing the position of the source in relation to the observer’s line of sight (LOS). The next sections discuss the position index, the human field of view, and the impact of the source spectral power distribution (SPD), participant age, and eyeglass wearing on discomfort glare.

Luckiesh and Guth developed the position index (P), which is widely used in discomfort glare models, to represent the relative impact due to the source position (Luckiesh and Guth 1949). The position index of a source is the ratio between the luminance of an off-axis source and the luminance of a reference, provided that both luminances provide the same sensation of brightness. The position index—as devised by Luckiesh and Guth—is lowest for an on-axis source and increases as the eccentricity increases. In this context, eccentricity is the angular displacement of a light source from LOS, irrespective of the direction of the displacement. The position index value is inversely correlated with the amount of discomfort glare, meaning that a larger value indicates less glare compared to an on-axis source. The unified glare rating

(UGR) (Commission Internationale de l'Éclairage 1995) and the daylight glare probability (Wienold and Christoffersen 2006) use the position index to predict glare for sources in various positions in the field of view.

To develop the position index, Luckiesh and Guth utilized a hemispherical apparatus to conduct an experiment where they set the background luminance (L_b) to 34 cd/m^2 and varied the position of the source vertically (0 to 60°), horizontally (0 to 100°), and diagonally (0 to 70°). The central source in the hemisphere served as a reference and was set to a borderline between comfort and discomfort (BCD) luminance of 2,844 cd/m^2; this is the geometric mean BCD for a group of 50 participants. Each source was 0.0011 sr in solid angle and could be adjusted up to a maximum luminance of approximately 102,788 cd/m^2.

With the reference and off-axis sources (test sources) alternating, and using a subset of 10 participants, each participant adjusted each test source to match the same initial sensation of brightness as the reference. That is, they determined a luminance value for each source that is equivalent in sensation to the reference (which was set to BCD luminance). These luminance values were divided by the luminance of the reference to obtain the position index. The position indices of sources located 20°, 40°, and 60° vertically above the LOS were 2.1, 5.4, and 16.9, respectively. Figure 1 shows the position indices for the complete set of sources positioned directly above the reference.

A more recent study used the same source size and background luminance as Luckiesh and Guth and involved 27 participants, none of whom wore eyeglasses (Kim *et al.* 2009). With the on-axis reference set to BCD (2,590 cd/m^2), the luminance of the test source was gradually increased from 0 while alternately flashing at 1 second intervals with the on-axis reference. When the luminance of the test source reached a point with the same sensation as the reference, the subject verbally announced reaching that level. This study used halogen lamps for the test and reference sources with a range of 0–160,000 cd/m^2. While the overall relationship between the position index and vertical angle was similar to that by Luckiesh and Guth, their position index values were consistently lower (Fig.1). The authors did not speculate on the reason for this difference in position index values.

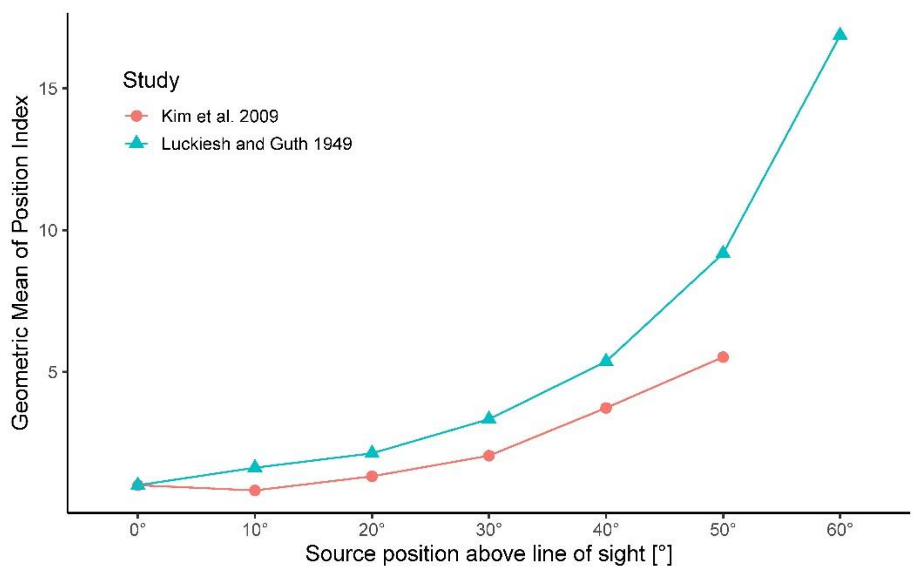


Fig.1: Position index as a function of the angle above LOS, using the luminance of the on-axis source as a reference. Data from Luckiesh and Guth 1949 and Kim *et al.* 2009.

The studies by Luckiesh and Guth (1949), and Kim *et al.* 2009 have limitations that should be considered: 1) both studies did not test sources located more than 60° and 50° above the LOS, respectively; 2) Luckiesh and Guth collected data from a limited sample of ten subjects; out of these ten subjects, only four were able to evaluate the source located 60° above LOS; 3) the sources could be adjusted up to a maximum luminance that is well below the luminance of modern LEDs, which can exceed a million cd/m^2 with a diameter much smaller than the 0.0011 sr source size used in the earlier experiments; 4) anchor bias might have affected the results because these studies only used one starting luminance value for each condition; 5) Luckiesh and Guth only evaluated the impact of L_b on BCD for the on-axis source; the position index values were derived under one L_b level (34 cd/m^2) and it remains unclear if the position index is affected by L_b.

Currently, the position index is applied to sources regardless of background luminance including nighttime applications for pedestrians and drivers (Abboushi and Miller 2022). Luckiesh and Guth (1949) showed a liner relationship between BCD and background luminance, which implies that the position index is constant regardless of background luminance. Research studies examining discomfort under low luminance levels ~1 cd/m^2 would benefit from research confirming that the position index values hold under these lighting conditions.

1.1. Field of view

The studies by Luckiesh and Guth and Kim *et al.* limited their evaluations to sources within the field of view; this assumes that sources outside the field of view do not cause discomfort glare. Technically, the human visual field extends about 55° above the point of fixation (assumed to be parallel to the ground plane), 70° below, and slightly more than 100° both to the left and the right of the point of fixation as shown in Fig.2 (left). The binocular visual field varies slightly according to an individual's facial structure, which has been suggested to influence discomfort glare (Ngai and Boyce 2000). It has been commonly assumed that once the light source was positioned outside this field where objects are not imaged on the retina, it no longer caused discomfort, but experience and research suggest otherwise.

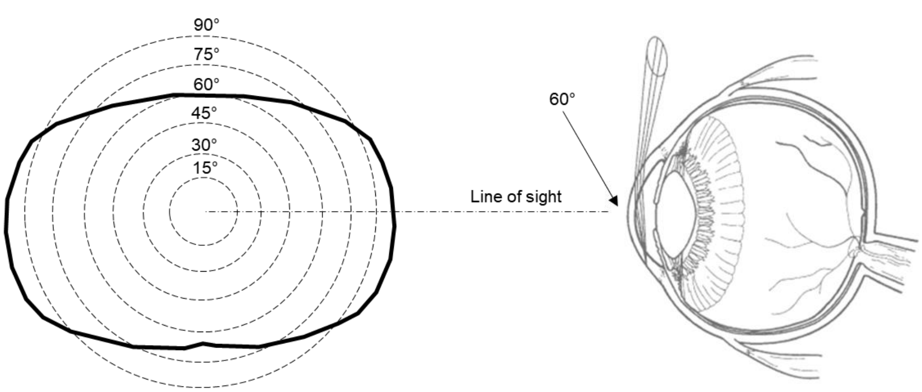


Fig.2: Left: human binocular field of view adapted from (Ruch et al.). Right: an illustration of oblique optical rays that can be refracted through the eye, known as the Coroneo effect, adapted from (Sliney 1999). The 60° line is shown for reference as that is the highest vertical angle included in the Luckiesh and Guth position index (1949).

In this article, sources positioned 60° or higher from LOS are referred to as overhead light sources. Ngai and Boyce (2000) explored overhead glare and showed that approximately 20% to 70% of participants experienced visual discomfort when the luminaire was at vertical angles between 65° and 85° from the LOS. Luminaires outside the field of view may still cause visual discomfort because the light is transmitted into the observer's eye from an oblique overhead angle as shown in Fig.2 (right), through the eyelid and eyebrow, or reflected from the observer's cheeks and nose. It is important to note that scattered or reflected light can reduce visibility, hence it is not possible to fully separate discomfort glare from disability glare.

Overhead glare may be experienced outdoors on sunny days where it is often mitigated with a brimmed hat, at night under intensely bright streetlights that are nearly overhead, or indoors under high-intensity industrial luminaires and even some recessed downlights. However, current practice does not consider sources close to 60° above LOS because they are positioned above the observer's visual field and may be hidden by eyebrows and forehead (CIE 1995).

1.2. Spectral power distribution

Multiple studies have indicated an association between discomfort glare perception and light source SPD, and more specifically increasing as short-wavelength content increases (Bullough *et al.* 2002; Van Derlofske *et al.* 2004; Sivak *et al.* 2005; Bullough 2009; Sweater-Hickcox *et al.* 2013; Zhang *et al.* 2013). Zhang *et al.* found that fluorescent luminaires with a correlated color temperature (CCT) of 6300 K positioned at 55° above the LOS to be more glaring than the same luminaires at 4000 K, the principal difference being the increased radiance from 400 nm to 540 nm. The effect was small but statistically significant and independent of increased luminance.

Sivak *et al.* (2005) examined glare response due to short-wavelength content in headlights using a range of LED and conventional sources (tungsten-halogen and high-intensity discharge). They tested five lamp types and three levels of illuminance at the eye. In each trial, each source was presented for three seconds; the transition time was not reported. They used the S-cone spectral weighting of the SPD as a measure of short-wavelength content and found that ratings of discomfort glare were linearly associated with the blue content as defined by S-cone weighting, with higher blue content resulting in ratings of greater discomfort. Van Derlofske *et al.* (2004) also found the spectral content to affect discomfort glare from auto headlamps, but not disability glare.

1.3. The effect of age and optical corrections

Two common individual factors that might affect discomfort from glare are age and wearing of eyeglasses. With age, the transmittance of the ocular media declines due primarily to the crystalline lens becoming cloudier and more yellowed, plus a progressive reduction in pupil diameter. By the age of 60, the crystalline lens of an average person transmits less light compared to age 20, varying by wavelength (e.g., 50% at 450 nm, 89% at 550 nm, and 96% at 650 nm) (Eto et al. 2020; Eto and Higuchi 2023). This is in addition to the reduction of retinal illuminance from the reduction in pupil size, and contrast loss due to increased light scatter (IES 2020a). The increased intraocular scatter leads to greater glare sensitivity, and the smaller pupil cannot contract enough to reduce the offending direction of light.

Regarding eyeglass wearing, preliminary testing conducted by the authors suggested that the wearing of eyeglasses may affect the glare perception from overhead sources. This is due to potential shadowing by eyeglass frame and flare reflections through the lens and off the bottom of the eyeglass lens.

A previous review (Pierson *et al.* 2018) found inconclusive evidence that age affects discomfort glare; the review also suggested that optical correction was unlikely to affect glare perception. Exploration of these factors was warranted for the current study.

1.4. Hypotheses

This manuscript documents an experiment that used a hemispherical apparatus, similar to that used by Luckiesh and Guth (1949), to further investigate the effects of light source position, background luminance, and SPD on discomfort glare using two different procedures. We hypothesized that:

1) Overhead light sources located 60° or more above the LOS would be detected and their position index could be quantified.
2) Discomfort matching procedure and the BCD adjustment procedure would provide similar position indices. This was hypothesized following recommendations to conduct glare evaluations using more than one procedure (Fotios and Kent 2020).
3) Position index values would be similar for low and high background luminance (1 cd/m^2 and ~34 cd/m^2, respectively).
4) BCD luminance values would be higher for sources with lower blue content (*i.e.*, warm SPD), compared to a cool SPD because participants will find them less glaring at an equal photopic luminance.
5) Older subjects (55+ years old) would have lower position index and BCD values compared to younger subjects (18–30 years old) because they experience more intraocular scatter and are thus more sensitive to discomfort from glare.
6) For overhead light sources, participants wearing eyeglasses would have different BCD luminance values and position indices than those without eyeglasses.

2. Methods

The experiment was performed using a custom hemispherical apparatus (Labsphere Inc.), similar to that used by Luckiesh and Guth (1949), with the participant's LOS horizontal, and test source locations mounted in different positions relative to participant's eye position. Two procedures were used in this experiment: a discomfort level matching procedure and an adjustment procedure to set the brightness at the BCD. Six test light sources at different positions were included in the matching procedure, and five test sources were included in the BCD procedure. Source positions included those 60° or more above the participant's fixed horizontal axis of view, some mounted vertically directly in line with the participant's gaze, and some located to the participant's left or right at a 45° or 67.5° azimuth angle. The reference test source for the matching procedure was located 20° above the participant's LOS, rather than at (0°,0°), to reduce visual discomfort from fixation at the light source.

2.1. Apparatus

The physical apparatus was an integrating hemisphere with a radius of 0.96 m as shown in Fig.3 (left). The interior finish was a durable 18% flat gray Permaflect coating. A chinrest at the center of the hemisphere positioned participants' eyes at the center of the sphere with their view horizontal toward the fixation point at (0°, 0°) inside of the hemisphere. The participants used a rotary knob and button to control the luminance of the test source and to advance to the next stimulus.

A total of 48 holes in the hemisphere were equipped with tunable five-primary LED modules (Lumenetix CTM 119, 12.5 W, 1000 peak lumens) with a 22 mm diameter aperture, selected for its color-mixing characteristics and range of output. Five tunable 30.5 cm linear modules were mounted on the back side of the front wall of the hemisphere, hidden from view, in order to provide uniform background lighting (see Fig.S1 in supplementary materials for spot luminance measurements). Each module's spectrum and intensity were controlled through an 8-bit DMX signal with 256 steps. Luminance and spectral characteristics were carefully measured using Jadak PR-670 and correlated to DMX values in order to achieve consistency among different modules (see supplementary materials Figures S2 and S3).

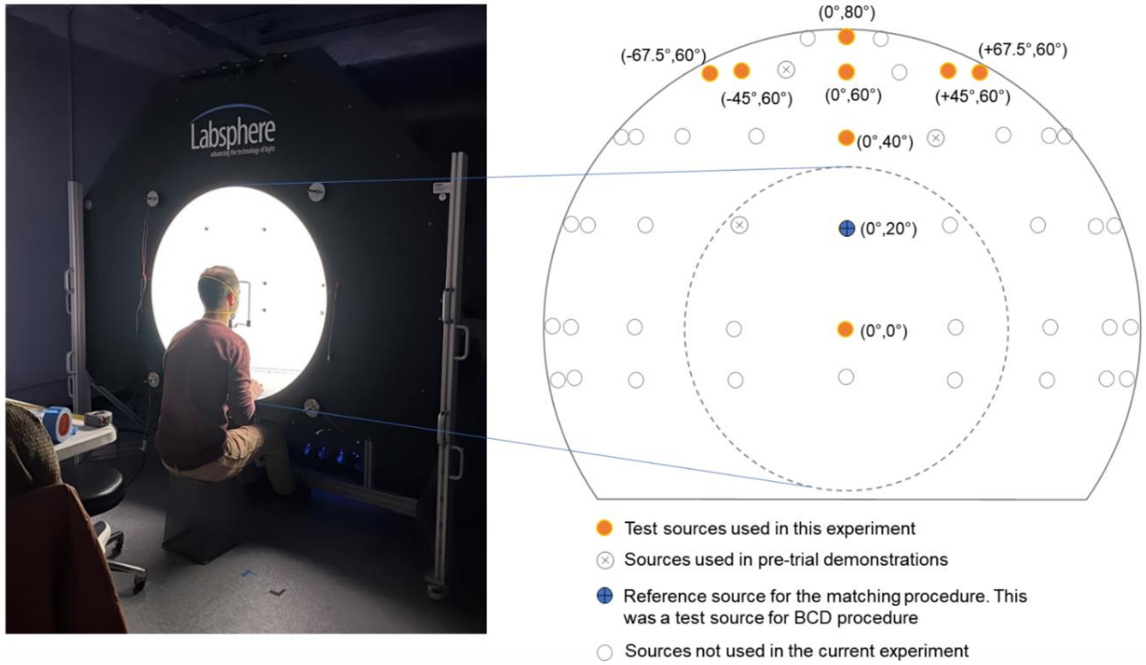


Fig.3: Photo of the apparatus (left) and a diagram of its source positions (right). The angles shown for each source represent the azimuth and elevation angles (azimuth, elevation). The diagram of source positions is presented from the perspective of the participant looking into the hemisphere.

2.2. Lighting conditions

Light sources were located at various elevations and azimuth angles as shown in Fig.3 (right). For this study, a subset of these sources was used, which will be referred to using the azimuth and elevation angles (azimuth, elevation). The sources were located at (0°, 0°); (0°, 20°); (0°, 40°); (0°, 60°); (±45°,60°); (±67.5°, 60°); (0°, 80°). An additional set of three sources were used in the pre-trial demonstration: (-22.5°, 20°); (22.5°, 40°); (-22.5°, 60°). Sources positioned to the left or right of the participant with the same horizontal displacement are referred to as one source (using the symbol ±) since these sources have the same position, symmetrically located within the field of view.

Table 1 shows the experimental conditions used in each procedure. In the matching procedure, the number of conditions was 24 (6 test sources x 2 background luminance levels x 2 anchors). In the BCD procedure, the number of lighting conditions was 40 (5 test sources x 2 background luminance levels x 2 anchors x 2 SPDs). For the matching procedure, the reference luminance values were calculated and set to target a UGR of 21 which represent a BCD value because a UGR value of 19 represents 'just acceptable' and a UGR value of 22 represents 'unacceptable' level of discomfort (Ashdown 2005). (The mean UGR value would have been 20.5, but was rounded up to the value of 21.) Actual UGR values were in the range 21 to 22 because of differences between the initial DMX-luminance 2-degree polynomial models used to determine the target DMX values and the revised models with higher polynomial degrees.

The reason the initial models were revised is because after data were collected, further examination of the initial 2-degree models showed that the data could benefit from further increase in polynomial degrees to fully capture the non-linearity between luminance and DMX, especially at low DMX values. For example, for the source at 0°,20° at the Cool SPD setting, the old model had high residuals of about 5000-7500 cd/m^2 at DMX values of 1 and 5. This old model was underpredicting luminance at DMX=1 and overpredicting at a DMX=5. The new spline-type models (Fig. S2 and S3) force the fit line to go through the measurement points (residuals=0).

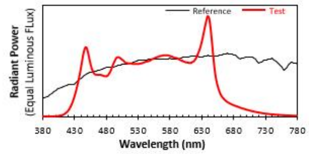
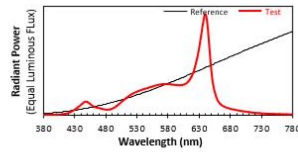
The order of procedures (matching or BCD), test sources, background luminance, and CCT were randomized across participants. To minimize any potential bias related to the position of the test source, test sources with positions on the left and right (±45°, 60° and ±67.5°, 60°) were counterbalanced across participants. For instance, under a certain background luminance level, a subject saw only (+45°, 60°) or (-45°, 60°), but not both.

To mitigate anchor bias, each lighting condition was evaluated twice, once starting from a preset high luminance value, and again from a preset low luminance value (Fotios and Kent 2020). Further information about the anchors is in supplementary materials Table S1. For each test source, the estimated luminance that would yield a UGR value of 21 was calculated, and anchor values were established by multiplying that estimated luminance by a high factor of 7 and low factor of 1/7. This factor was selected to place the anchors as far as possible from expected BCD within the available luminance range of the light sources. Table S1 shows target and actual anchor luminance values. The expected BCD value remained well within actual low and high anchor luminance values and the participants were able to adjust the luminance higher or lower from either anchor. The decision to use spline-type models allowed for a better fit of luminance measurements vs. DMX values, but it also meant that the derived anchor luminance values from these new models did not match those initially targeted.

At the lowest non-off signal level (DMX=1) and without applying any neutral density filters, the sources' luminance was approximately 10,880–12,285 cd/m^2, averaged across the test sources. In order to achieve an appropriate range of luminances from the sources located closer to the LOS one or two neutral density filters (LEE Filters) were used for sources (0°, 0°), (0°, 20°), (0°, 40°), and the two sources used for pre-trial demonstration (-22.5°, 20°) and (22.5°, 40°). The total transmission of filters was 3.4%, 13.7%, and 26.2% for sources at 0°, 20°, and 40° elevations, respectively. Further information about the used filters is in supplementary materials Table S2.

Table 1: The experimental conditions used in the matching and BCD procedures. The source size was the same for both procedures (0.0004 sr).

	Matching procedure	BCD procedure
Test source positions	Six test sources: (0°, 0°); (0°, 40°); (0°, 60°); (±45°, 60°); (±67.5°, 60°); (0°, 80°)	Five test sources: (0°, 0°); (0°, 20°); (0°, 40°); (0°, 60°); (0°, 80°)
Background luminance (L_b)	High L_b: 35 cd/m^2 (*SD*=8) Low L_b: 1 cd/m^2 (*SD*=0)	High= 35 cd/m^2 (*SD*=8), cool SPD High= 36 cd/m^2 (*SD*=9), warm SPD Low= 1 cd/m^2 (*SD*=0)
Reference source position	(0°, 20°)	-
Reference source luminance	28,400 cd/m^2 for high L_b, 4,347 cd/m^2 for low L_b	-
CCT of test source	Cool= 4551 K† (*SD*=227)	Cool= 4551 K† (*SD*=227) Warm = 2502 K† (*SD*=64)

<table>
<tr><td>SPD of test source</td><td>Cool SPD only</td><td>Both cool SPD (left) and warm SPD (below)</td></tr>
<tr><td></td><td>
</td><td>
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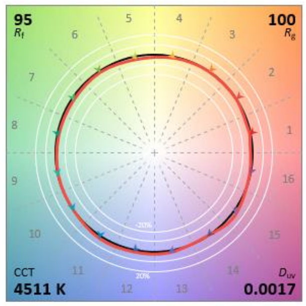
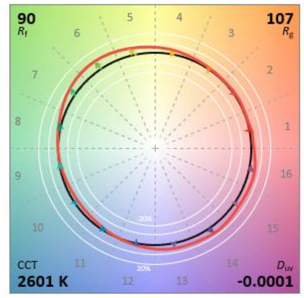
<tr><td></td><td>
</td><td>
</td></tr>
<tr><td>CCT of background‡</td><td>Cool CCT = 4427 K, 4532 K under high and low L_b, respectively</td><td>Cool= 4427 K, 4532 K for high and low L_b, respectively
Warm= 2473 K, 2465 K for high and low L_b, respectively</td></tr>
</table>

SD refers to the standard deviation of the source measurements.
† The mean CCT of all test sources and the reference each measured at nine levels of intensity output.
The dash (-) indicates that there is no reference source used in the BCD procedure.
‡ The CCT of background sources was measured using a spectrophotometer placed at the viewing location of the hemisphere.

2.3. Dependent measures

Two evaluation procedures were used in the experiment: a matching procedure and a BCD determination procedure. The dependent measure was the luminance of the adjustable test light source. In the matching procedure, each subject was asked to use the rotary knob to adjust the brightness of the test source to match the level of discomfort caused by the reference source located at (0°, 20°). For the BCD procedure, BCD was defined as the point of change between comfortable and uncomfortable light intensities; if the test light source was any brighter it would start to be uncomfortable (Lulla and Bennett 1981). The term *brightness* was intentionally used as a colloquial proxy for luminance because it incorporates the perceptual response to the luminance. The participant controlled one test source at a time to find the BCD. For both procedures, the light level was recorded as a DMX value and translated to luminance using the module DMX-luminance characterization curves. To create comparable data sets from matching and BCD procedures, both BCD data and matching luminance data were converted and represented as luminance ratios (*i.e.*, as a position index) of the test source compared to the (0°, 20°) reference source. Unless otherwise stated, the two luminance values (using high and low anchors) established by a participant for each test condition were averaged and used in the analysis.

2.4. Procedure

Participants completed the experiment one at a time. Each participant was led to the test room where they were asked to review and sign the informed consent form. The participant then underwent a facial scan to document the geometry of their face (POP 2 3D scanner). This was done to explore whether the facial geometry affects perception of overhead glare as postulated in previous work (Boyce et al. 2003). Data from the 3D scanner are not included in the scope of this article. Then, the participant was seated at the apparatus and was asked to keep their gaze fixated at the source (0°, 0°); the source was switched off and only the background luminance was turned on for adaptation. At that point, the room's ambient lights were turned off. Participants that typically wore eyeglasses were instructed to wear them during the experiment. At the beginning of each procedure, three pre-trial demonstrations were conducted to familiarize participants with the procedure and answer any questions they might have had.

For the matching procedure, the test and reference light sources were alternated (2s on – 2s off) so that the discomfort level of the two could be matched. This flashing technique is used to maintain participant's adaptation close to background luminance level, as done by Luckiesh and Guth (1949). The participant rotated a knob clockwise or counterclockwise to raise or lower the test light luminance. When the perceived discomfort from the test and reference sources matched, the participant pressed a button and the next pair of lights were presented. Figure 4 shows an example sequence of procedures and conditions.

For the BCD procedure, each participant was presented with a single test light at one position in the hemisphere that flashed 2s on – 2s off. There was no reference source in the BCD procedure. The participant raised or lowered the test source luminance until BCD was reached. The BCD conditions were completed under two SPDs (cool SPD with a CCT of approximately 4,500 K and a warm SPD with a CCT of about 2,500 K) and two L_b levels (1 cd/m^2 and 35 cd/m^2). A 2-minute adaptation period was included when switching between different levels of L_b or CCTs.

The knob could be spun in either direction without a hard stop. When a participant reached the end of the luminance range, the apparatus beeped indicating that the luminance could not be increased (or decreased) any further. The participants were asked to give a verbal indicator to the experimenter if they were reaching the end of the available luminance range and could not get the test source to be bright or dim enough to match or complete the BCD procedures. For the first few occasions when the apparatus beeped, the experimenter asked the participant whether they reached the maximum or minimum of the luminance range and were not able to complete an evaluation.

Participants were observed by the researcher using a camera mounted outside the hemisphere, facing inside through a hole, to ensure they were keeping their head level and gazing at the fixation point located at 0°, 0°. Photographs of the participant's face were captured at various timepoints throughout the experiment. At the end, participants were asked to complete a questionnaire to capture their experience with the experiment. Most participants completed the experiment in 1.5–2 hours.

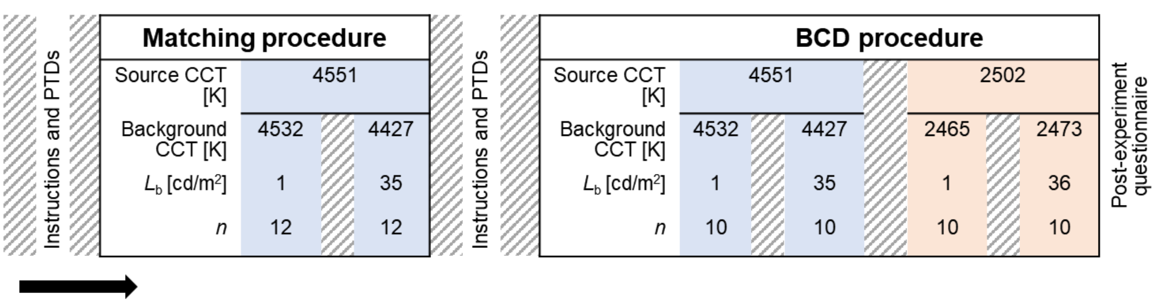


Fig.4: The overall sequence/timeline of experimental conditions. The blocks shaded with diagonal lines represent a 2-minute adaptation period for matching the SPD and L_b level of subsequent trials. Note that the order of procedures was counterbalanced between participants. The order of source and background SPD (cool or warm) was randomized within each set of trials, and the order of L_b (high or low) was randomized within each SPD condition. "n" refers to the number of scenes evaluated. PTDs are pre-trial demonstrations.

2.1. Participants

Participants were recruited through social media groups of surrounding communities, student groups and newsletters, consulting firms that participate in a local lighting society chapter, and word of mouth. A pre-screening questionnaire was sent along with recruitment material, which asked questions about participant's name, age, vision condition, history of migraines, their professional lighting background, and whether they were experiencing any COVID-19 disease or other illness symptoms. Participant age had to fall within the two targeted age groups, 18 to 30 and 55+ years old. Those that experience migraines were also excluded because the light modules used in the glare apparatus modulate in light output (*i.e.*, flicker) at 1,000 Hz. This restriction was done out of an abundance of caution because the stroboscopic effect and phantom array effect were barely noticeable as observed by the flicker-sensitive experimenters from the chinrest position, since there was no object movement in the hemisphere, and the eye movement was limited. Potential participants were also excluded if they were sick or experiencing COVID symptoms, could not walk up a flight of stairs to reach the experiment room, did not have normal 20/20 vision (uncorrected with glasses or contacts), could not get to the test site, or did not agree to have their face photographed by a camera or 3D scanner.

The Institutional Review Board at the Pacific Northwest National Laboratory reviewed and approved this study under protocol #2023-13. Blue light hazard calculations were conducted according to IES RP-27-20 Photobiological Safety of Lighting Systems (IES 2020b), determining there was little to no risk of retinal damage from blue light hazard for participants in this study. Participants received a $75 gift card as compensation for their time.

A total of 30 participants enrolled and completed the experiment. One participant's data were removed from analysis because the participant did not understand instructions for one of the conditions and did not use the dial to find the required brightness. This resulted in data from 29 participants being included in the analysis.

To test hypothesis 5, two disparate age groups were selected for comparison: 15 subjects were 21 to 30 years old, and 14 were 57 to 70 years old. This increased the likelihood that any significant difference in perception between the two groups was due to age rather than another undescribed variable.

To test hypothesis 6, about half of the participants recruited for each age group were those that typically wear glasses. This allowed for isolating the effect of wearing glasses (e.g., interior lens reflections or frames blocking light sources) within each age group.

3. Results

Instances where the participant was unable to find the matching or BCD luminance because they reached the maximum of the luminance range (n=68), minimum of luminance range (n=25), or could not notice the test source and skipped the scene in the matching procedure (n=3) were not included in the analysis. Table 2 shows the distribution of these cases by procedure, L_b level, and vertical angle of the source. As Table 2 shows, there were a larger number of participants who reached the max limit and were not able to evaluate glare at (0°, 80°) compared to other test sources with lower elevation angles. The number of cases where participants reached the max limit was also higher under high L_b compared to low L_b.

Table 2: The distribution of cases where participants reached the maximum (Max limit) or minimum (Min limit) of the available luminance range, respectively, and were unable to complete the glare evaluation for a given condition. The total number of cases were 696 and 1160 for the matching and the BCD data sets, respectively. The source at 20° served as a reference for the matching procedure, hence was not evaluated as a test source.

		High L_b					Low L_b				
		Elevation angle					Elevation angle				
		0°	20°	40°	60°	80°	0°	20°	40°	60°	80°
Matching	Min limit		-		1		1	-	1	3	
	Max limit	1	-		2	10		-			
	Skipped		-		1			-		1	1
BCD	Min limit		3				2	10	1	3	
	Max limit		1	6	7	31					8

Consistent with Luckiesh and Guth (1949), the geometric mean of the position index values is used in this study because it is less affected by extreme values compared to the arithmetic mean. The arithmetic mean and standard errors are still helpful to show the uncertainty (see Fig.S4 for arithmetic means and standard errors). To calculate the geometric mean of position index from the matching procedure, the position index values were first calculated for each participant by dividing the arithmetic mean luminance of the test source (from high and low anchor trials) by the luminance value of the reference at (0°, 20°) which was 28,400 cd/m^2 for the high L_b and 4,347 cd/m^2 for the low L_b scenes; these position index values were then used to calculate the geometric mean across participants. For the BCD procedure, the geometric means were similarly calculated except that the initial step involved dividing the arithmetic mean luminance of the test source by the arithmetic mean luminance of the (0°, 20°) source because the BCD luminance of the (0°, 20°) source was set by each participant in this procedure. Fig.5 shows geometric mean position index values from the matching and BCD procedures, compared to the module at (0°, 20°). Table S3 shows the geometric mean values and standard deviation by each variable.

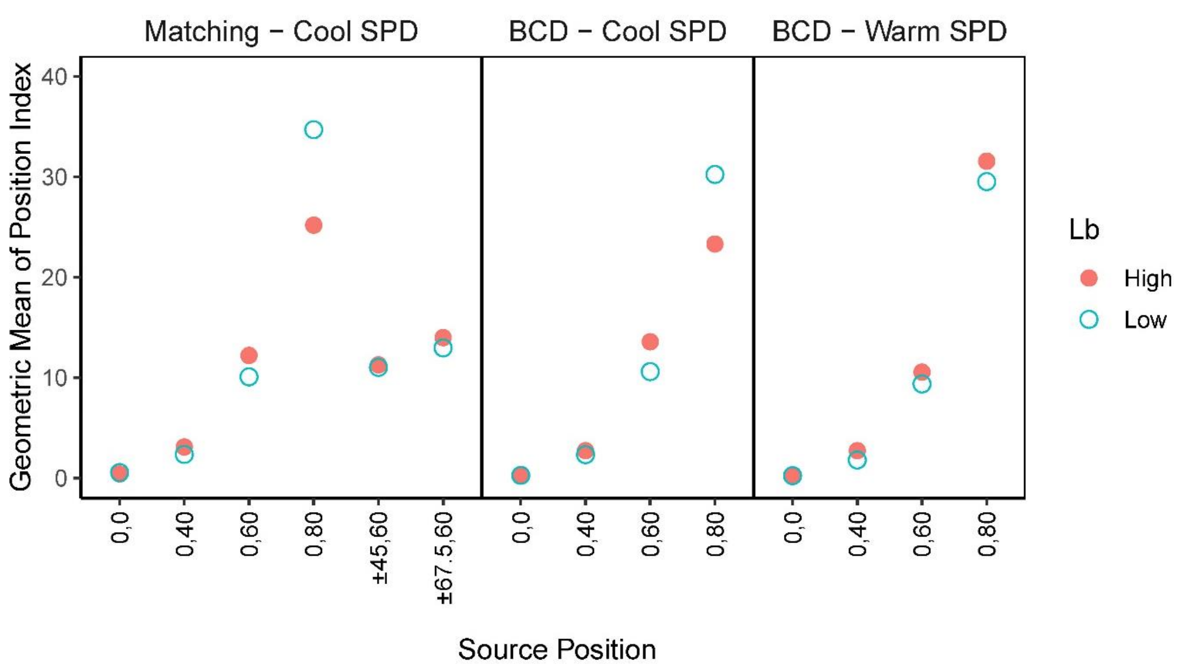


Fig.5: Geometric mean position index values from the matching and BCD procedures using the source at (0°, 20°) as a reference, shown by background luminance.

To evaluate the hypotheses, the use of parametric tests was first explored by checking the normality assumption, e.g., paired T-test, was evaluated using histogram plots and the Shapiro-Wilk tests, which showed that the data were not normally distributed. Hence, alternative non-parametric tests were used to test the hypotheses for significance at the 5% and 1% levels.

3.1. The impact of the test sources located at (0°, 80°) and (0°, 60°)

Table 3 shows geometric mean position index values from the matching and BCD procedures for overhead sources compared to the reference at (0°, 20°). Consistent with the position index values from Luckiesh and Guth (which used a reference point of (0°, 0°)), we found that the position index values were similar for sources at 60° elevation regardless of the azimuth angle. Overall, the position index values for the source at (0°, 80°) elevation were about 2-3 times higher than those for the source at (0°, 60°). These results support hypothesis 1 that expected the overhead test sources to be detectable, and their position index to be quantifiable.

Table 3: Geometric mean of position index and luminance values of the test sources at 80° and 60° elevation angles calculated using the reference at (0°, 20°) under high and low background luminances.

Test source position	**Procedure and SPD**	**Geometric mean of position index**		**Geometric mean of test source luminance [cd/m^2]**	
		High L_b	**Low L_b**	**High L_b**	**Low L_b**
(0°, 80°)	Matching – cool SPD	25.2	34.7	715,193	150,829
	BCD – cool SPD	23.3	30.2	794,777	254,734
	BCD – warm SPD	31.6	29.5	864,464	241,460
(0°, 60°)	Matching – cool SPD	12.2	10.1	346,735	43,804
	BCD – cool SPD	13.6	10.6	417,723	82,519
	BCD – warm SPD	10.5	9.4	386,977	87,501
(±45°, 60°)	Matching – cool SPD	11.3	11	320,028	47901
(±67.5°, 60°)	Matching – cool SPD	14	13	397,187	56,337

3.2. Comparing position index values by procedure

Hypothesis 2 was that the two experimental procedures would yield similar position indices. This was tested by comparing between the matching and BCD procedure with cool SPD (using the common test sources with 0° azimuth). A paired Wilcoxon signed rank test with continuity correction did not show a significant difference in position index values between the two procedures under either L_b condition. Figure 6 shows the position indices with the reference being at (0°, 20°). This finding supports hypothesis 2 in which we expected the two procedures to converge and provide similar position indices. Note that the position index values from the matching procedure are not directly comparable to those from Luckiesh and Guth (1949) or Kim et al. (2009) because their reference was at (0°,0°) compared to the reference in this study at (0°,20°).

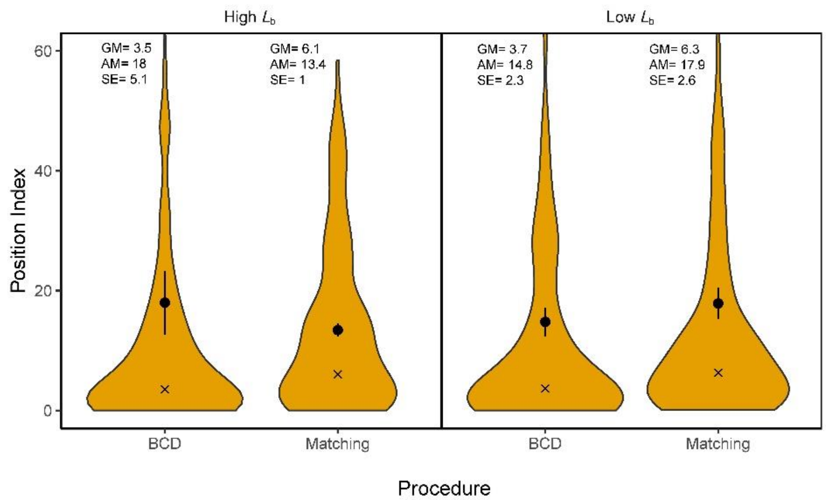


Fig.6: Violin plots showing the position index values by procedure and background luminance level (high or low L_b). Note that the data shown in this figure includes only the common source locations between the two procedures: excluding data sets from positions such as (+/- 67.5°, 60°), (+/-45°, 60°), and (0°, 20°). The solid circles represent the arithmetic means (AM), and the bars represent the standard error (SE) of the mean. The x symbol represents the geometric mean (GM).

3.3. Analysis by L_b

A Wilcoxon signed rank test with continuity correction did not show a significant difference in position index values from the matching procedure between the high and low L_b levels (Fig.7). Likewise, the difference in position index values from the BCD procedure between the two L_b levels was not significant under either cool or warm SPD. This supports hypothesis 3 indicating no difference in position indices by background luminance level.

In line with findings of previous studies on glare (Luckiesh and Guth 1949), the Wilcoxon signed rank test with continuity correction showed that BCD luminance values with high L_b were significantly higher than with low L_b ($p<0.01$).

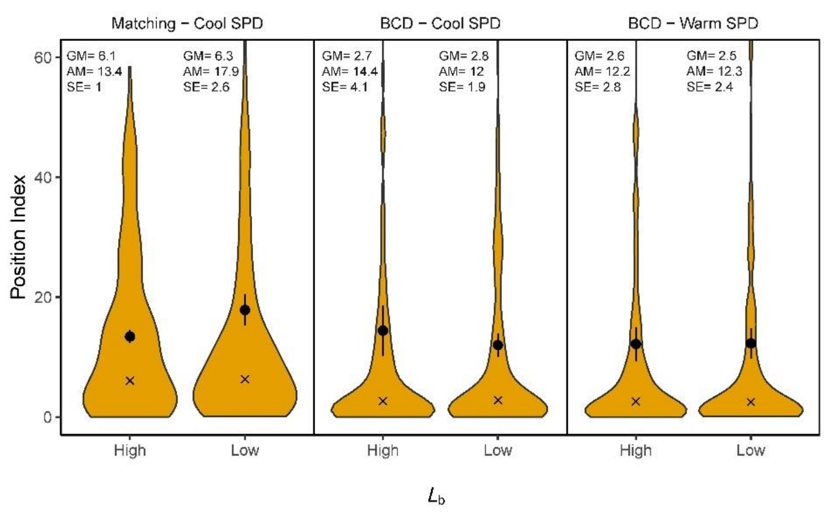


Fig.7: Violin plots of position index values from the matching procedure (left) and position index values from the BCD procedure (middle and right for cool and warm SPD conditions, respectively) by background luminance level (high or low L_b). The solid circles represent the arithmetic means (AM), and the bars represent the standard error of the mean (SE). The x symbol represents the geometric mean (GM).

3.4. Analysis of BCD ratio and values by CCT

A Wilcoxon signed rank test with continuity correction showed no significant difference in position index values or in BCD luminance values between cool and warm SPD (Fig.8). This applies to comparisons using low or high background luminance conditions. This does not support hypothesis 4 where the cool SPD was expected to have lower BCD luminance values.

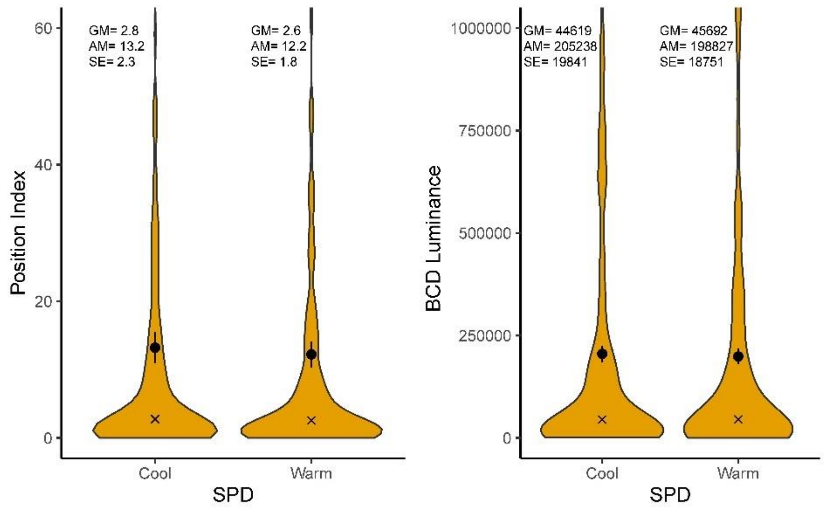


Fig.8: Violin plots of position index values from the BCD procedure by SPD (left) and BCD luminance value by SPD (right). The solid circles represent the arithmetic means (AM), and the bars represent the standard error of the mean (SE). The x symbol represents the geometric mean (GM).

3.5. Examining differences in position index values and BCD luminance by age group

A Wilcoxon signed rank test with continuity correction did not show significant differences in position index values from either procedure or in BCD values between the two age groups (55+ compared to 18-30) for either L_b level. This finding does not support hypothesis 5 where we expected older participants to have lower position index and BCD luminance values, compared to the younger participant group.

3.6. Examining differences in position index values and BCD luminance by eyeglass wearing

A Wilcoxon signed rank sum test with continuity correction did not show any significant differences in position indices from either procedure or in BCD values of test sources at (0°, 80°) and (0°, 60°) between participants that wore glasses and those that did not. This does not support hypothesis 6 that expected participants who wear glasses to have different position index values and BCD luminance, compared to participants who do not wear eyeglasses.

4. Discussion

The two procedures used in the experiment consistently showed that sources positioned 60° or 80° above the LOS can be detected and their position index can be quantified. The position index values found in this study were higher compared to those previously reported by others (Luckiesh and Guth 1949, Kim *et al.* 2009) (Fig.9). For example, for a source 60° directly above LOS, Luckiesh and Guth found that geometric mean of the position index was16.9, compared to 53 found in the current study using the BCD procedure for the cool SPD, L_b of 35 cd/m^2, and normalizing to the (0°, 0°) source — not the (0°, 20°) source — for consistency with previous studies. This difference may be due to the smaller source size used in the current study (0.0004 sr), which is about 1/3rd of that used in the two previous studies (0.0011 sr).

The position index values calculated from the matching procedure cannot be directly compared to previous studies that used a different reference. Had the reference been set at (0°,0°) for the matching procedure in our study, we would expect the matching position index values to be higher than the current results based on a 0,20 reference. One we established that the position index values did not vary by procedure, we then only used the BCD procedure results for comparison with Luckiesh and Guth (1949) and Kim et al (2009) as shown in Fig.9.

If the impact of the source size is consistent for test sources at different positions, we would expect the position index values to relate to those from Luckiesh and Guth using a constant factor. However, as shown in Fig.9, the difference between this study's position index values and those from Luckiesh and Guth position, increased as vertical angle increased. The position indices shown in Fig.9 suggest a potential interaction between the source size and the position index such that a smaller source, such as the one used in the current study, would have to be at higher luminance values to achieve the same sensation of discomfort as an on-axis reference, compared to a larger source in the same position. Similarly, the position index values for a larger source, like the one used by Boyce *et al.* (2003) and Ngai and Boyce (2000), are expected to be lower, compared to a smaller source in the same position.

To examine the possibility of a potential interaction between position index and source size, consider the studies by Ngai and Boyce (2000) and Boyce *et al.* (2003). Ngai and Boyce examined BCD luminance of a 0.10 m (4") wide x 1.19 m (47") long luminaire aperture with diffuse distribution. The luminaire was mounted on ceiling tracks with the aperture parallel to the floor and could be repositioned closer or farther way from the subject, at angles of 55°, 65°, 75°, 85° and 95° above the LOS. The aperture was mounted at 2.4 m (8') height above the floor. Under the low ambient illuminance condition, the wall area seen by the participants when looking straight ahead measured approximately 30 cd/m^2; this background luminance level is similar to this study's 35 cd/m^2 high L_b condition. We calculated the luminance ratio between sources that elicited a BCD sensation of 3.5 rating on their 7-point scale (Fig.2 in their article). The luminance ratio between the source at 75° and 85° in relation to the source at 65° were 1.6:1 and 3.3:1, respectively. Note that due to the use of ceiling tracks to move the source, the source size was not controlled and became smaller at lower elevation angles. For example, the projected solid angle of the source at 65° is smaller compared to 85°.

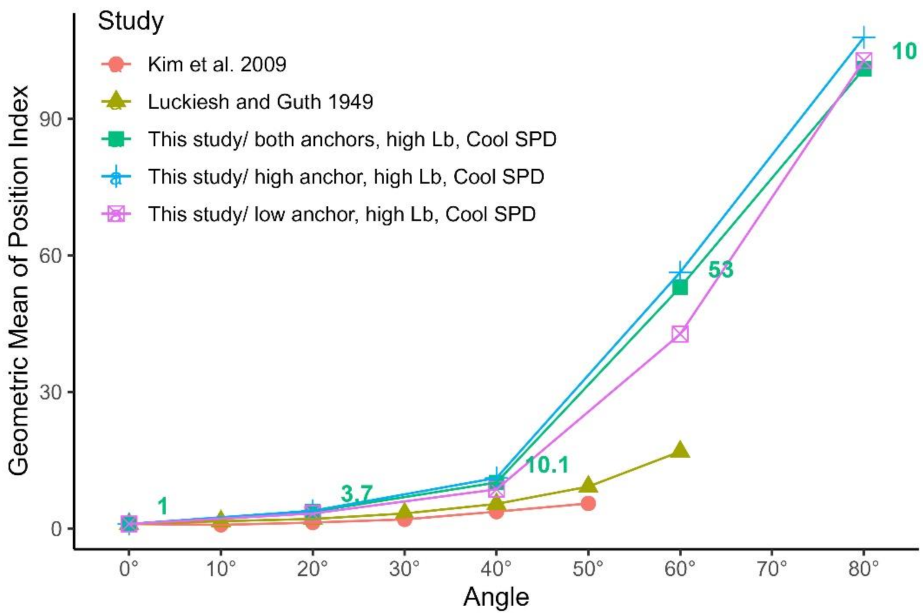


Fig.9: The geometric means of position indices for this study, Luckiesh and Guth (1949), and Kim *et al.* (2009). To compare the position index values from the current study to previous studies, the position index values for this figure use BCD procedure data with cool SPD and high L_b. Note that these values use an on-axis source (0°, 0°) as a reference for normalization (as used in the two previous studies), thus they differ from those reported in Table 3. The numbers shown on the graph are the position index values from this study using both anchors.

In a subsequent study that used a similar experimental setup, but controlled the source size (Boyce *et al.* 2003), the luminance ratio between sources at 75°, 85°, and 95° above LOS in relation to a source at 55° was 2:1 (see Fig.4/ top in Boyce *et al.* 2003). This ratio was calculated using luminance values eliciting a BCD sensation of 3.5 on the 7-point scale. This ratio is similar to the 1.6:1 luminance ratio between the (0°, 80°) source and the (0°, 60°) in the current study using data from BCD procedure with high L_b and cool SPD. While this does not support the possibility of an interaction, this comparison is limited and further testing is warranted. Regarding this potential interaction between source size and position index, it can be hypothesized that an overhead large source might have a smaller position index value compared to a smaller source in the same position.

In addition to the possibility of an interaction between source size and the position index, the position index data from Luckiesh and Guth and Kim et al. might be affected by anchor and range bias (Fotios and Kent 2020). To examine whether the use of two anchors, compared to one, influenced the position index values in the current study, we compared the position index values by anchor. For the matching procedure, a Wilcoxon signed rank test with continuity correction showed that the position index values using high anchors were significantly higher than those calculated using low anchors (p<0.01). We did not find a significant difference between position index values from high and low anchors using the BCD procedure. This is likely due to wider variation introduced using the BCD procedure compared to the matching procedure. Figure 10 shows the geometric mean position index values by anchor. This analysis shows that the use of two anchors is unlikely to be the main reason for differences in position index values between this study and Luckiesh and Guth's study. The wider luminance range used in the current study and the possibility of an interaction between source size and position index are the likely factors.

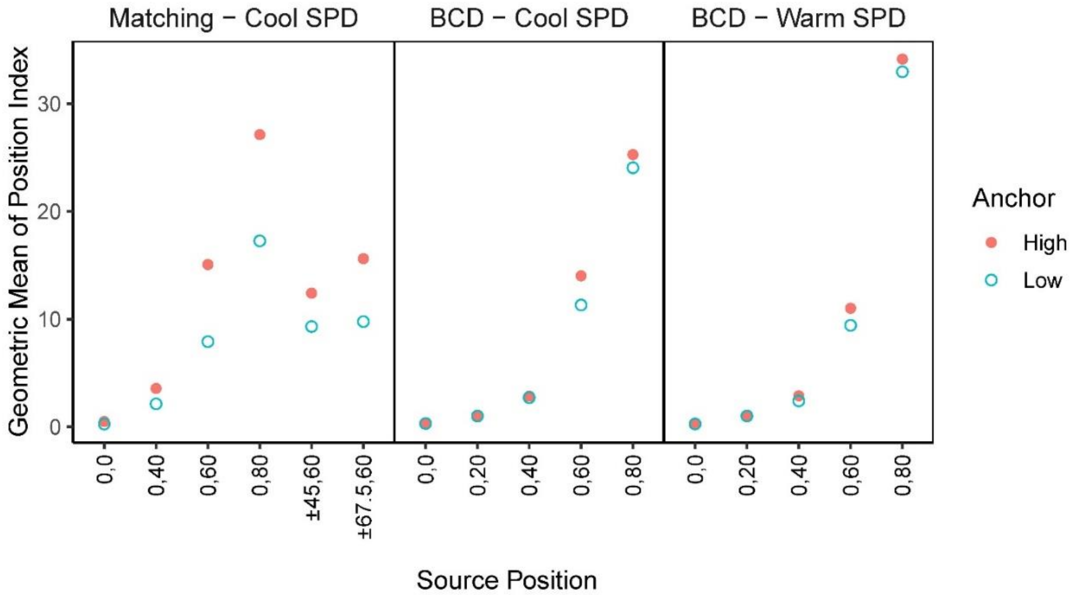


Fig.10: Geometric mean position index values by procedure, SPD, test source position, and anchor (high or low) for high L_b conditions only, and using the reference (0°, 20°) for the Matching procedure.

The Luckiesh and Guth work examined a range of round source sizes along the LOS: 0.0001 sr, 0.0011 sr, 0.0079 sr, 0.0314 sr, and 0.126 sr. This study's source falls between the two smallest of these, with a solid angle of 0.0004 sr. Luckiesh and Guth provided an equation relating BCD brightness *B* of a source in footlamberts, the size of source *Q* in steradians, and field brightness *F* in footlamberts as follows when the source is viewed on-axis:

$$B = 108\, F^{0.44} (Q^{-0.21} - 1.28) \qquad (1)$$

They found the BCD luminance of (0°, 0°) to be 2,844 cd/m^2 with a diameter of 0.0011 sr. Using their equation would predict that this study's BCD luminance at (0°, 0°) for the 0.0004 sr light source and high L_b to be 4,000 cd/m^2, which is lower than the BCD values found in this study at the same position. This might be due to differences in source size, luminance range, and anchor bias. A previous study found that range bias affects the luminance adjustment procedures (Kent *et al.* 2019). We implemented a best practice to mitigate range bias using the mean of two anchors as a best estimate (Fotios and Kent 2020). Table 4 shows a comparison between the current study and previous studies. Note that the BCD value in this study using only high or low anchor would shift the BCD value; the BCD value for the on-axis source using only the low anchor is closer to that estimated using (1).

Table 4: A comparison of luminance range anchors, source size and geometric mean of BCD for the on-axis source for this study for cool SPD with high L_b (using low, high, or both anchors) and two previous studies.

Study	Source size [sr]	Luminance range [cd/m^2]	Anchors	BCD [cd/m^2]
Luckiesh and Guth 1949	0.0011	0–102,788	One anchor†	2,844
Kim *et al.* 2009	0.0011	0–160,000	Low anchor	2,590
This study (BCD procedure with cool SPD)	0.0004	347–1,811,000	Low and high anchors	8,922
			Low anchor only	6,261
			High anchor only	10,638

† The authors did not report the anchor luminance.

Significant differences in BCD ratios or BCD values between warm and cool SPD conditions were not found in this study. This might be due to differences in the experimental procedure that led to a longer adaptation time in the current study, compared to previous studies where different SPDs were sequentially presented with a transition time ranging from 6 seconds to 1 minute (Berman *et al.* 1996; Sivak *et al.* 2005; Bullough 2009; Sweater-Hickcox *et al.* 2013). The current study grouped trials with the same procedure and SPD into three blocks that were randomly presented to participants (matching – cool SPD, BCD – cool SPD, and BCD- Warm SPD) with a transition time between 2–5 minutes. The chromatic adaptation of participants is critical in experiments examining lighting with different colors and can affect the external validity of findings (Fotios and Houser 2009; Royer *et al.* 2022). Royer *et al.* recommended a minimum of two minutes of chromatic adaptation if the chromaticity is being varied between stimuli. With longer adaptation time, we hypothesize that the impact of SPD on discomfort glare is attenuated, as suggested for the impact of SPD on brightness perception (Fotios 2006). In our case, it is possible that the longer adaptation time reduced the effect size such that a larger number of participants would be needed for detection.

LED products can exhibit very high luminance values. Even when used at high angles they can be uncomfortably bright. Some emitters measure at over 1,000,000 cd/m^2, although those luminances are usually reduced with the use of diffusing materials or indirect optical systems. The results of this experiment extend our knowledge of discomfort glare to LED products mounted at or above the field of view, such as industrial lighting, streetlights, canopy lighting, sports lighting, and even interior high intensity recessed downlighting with insufficient shielding.

5. Limitations

The results of the current study ought to be interpreted considering the following limitations:

- Not all source positions in the hemisphere were tested; this was decided to reduce participant's fatigue due to a long experiment time. Future studies are encouraged to test other test source positions and compare the position index to Luckiesh and Guth's data.
- Only two background luminance levels were tested, omitting higher levels that might be more typical in brightly lit architectural spaces, for example.
- The source size was limited to a 22 mm diameter source, and this does not represent a wide range of indoor and outdoor luminaires that may be much larger or smaller, or rectangular in configuration, for example.
- The source was uniform in luminance, so luminaires with patterns such as a cluster of LEDs, or a pattern of louvers were not evaluated.
- The subjects were directing their view horizontally at all times. Thus, we did not examine the effect of normal dynamic viewing situations (indoors or out) when the LOS moves up and down, left and right, to take in relevant information and focus on multiple visual tasks in multiple directions with multiple saccades.
- The participants did not have cognitive or other tasks to perform, which may affect the glare response.
- Migraineurs were excluded as potential participants, potentially limiting the subject pool to people less perceptually sensitive to glare or with no adverse physiological effects to glare.

6. Conclusion

The study investigated discomfort glare from overhead sources positioned 60° and 80° above LOS. These sources were detectable by almost all of the participants despite being at the edge or outside the field of view. These results support the inclusion of sources outside the field of view in discomfort glare metrics.

The current practice of using the same position index values regardless of source size warrants further studies. The results from this study showed that smaller sources (0.0004 sr) had higher position index values than those previously reported for a larger source (0.0011 sr) by Luckiesh and Guth. This suggests that Luckiesh and Guth's position index values might have been influenced by the use of one anchor and a limited luminance range, which can impact their applicability to current LED sources with potentially higher luminance.

By comparing the position index values found in this study to those reported by Luckiesh and Guth, we could not rule out the possibility that the position index interacts with source size. This means that smaller sources might be associated with larger position index values compared to larger sources; testing this using source size as a variable within an experiment is warranted.

We did not find significant differences in position index or BCD luminance by age group or eyeglass wearing. Lastly, this study calls into question the effect of SPD on discomfort glare. In contrast to previous studies that mostly used short adaptation times, we did not find a difference in BCD luminance or position index values between the warm and cool SPD. Future studies comparing longer vs. shorter chromatic adaptation periods are needed to evaluate sustained effects on discomfort glare.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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