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Preliminary evaluation of discomfort glare from organic light-emitting diode and edge-lit light-emitting diode lighting panels

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Abstract. The organic light-emitting diode (OLED) is an area light source, and its primary competing technology is the edge-lit light-emitting diode (LED) panel. Both technologies are similar in shape and appearance, but there is little understanding of how people perceive discomfort glare (DG) from area sources. The objective of this study was to evaluate the DG of these two technologies under similar operating conditions. Additionally, two existing DG models were compared to evaluate the correlation between predicted values and observed values. In an earlier study, we found no statistically significant difference in human response in terms of DG between OLED and edge-lit LED panels when the two sources produced the same luminous stimulus. The range of testing stimulus was expanded to test different panel luminances at three background illuminations. The results showed no difference in perceived glare between the panels, and, as the background illumination increased, the perceived glare decreased. In other words, both appeared equally glary beyond a certain luminance and background illumination. We then compared two existing glare models with the observed values and found that one model showed a good estimation of how humans perceive DG. That model was further modified to increase its power. © 2017 Society of Photo-Optical Instrumentation Engineers (SPIE) [DOI: [10.1117/1.JBO.22.5.055004](https://doi.org/10.1117/1.JBO.22.5.055004)]

Keywords: discomfort glare; edge-lit; light-emitting diode; organic light-emitting diode; indoor lighting; background lighting.

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1 Introduction

For decades, diffuse lighting panels have been used for ambient illumination or where a uniform luminous appearance is desired. Diffuse lighting panels typically have a diffuser material that is placed in front of one or more light sources to create a uniform appearance. Organic light-emitting diodes (OLEDs) are a type of area light source that do not require secondary optics to produce uniform, diffuse illumination. Commercial OLED technologies have been steadily evolving and now can be used in certain niche lighting applications. Presently, OLED panels with luminances exceeding 3000 cd/m^2 and efficacies exceeding 80 lm/W are commercially available and soon are expected to reach 190 lm/W with correspondingly higher luminances, as well as longer rated useful lifetimes.¹ One of the most commonly quoted benefits of OLEDs is their “soft” appearance, which makes them comfortable to look at because they do not produce glare.^{1,2} Edge-lit LED panels are a competing technology that can offer physical, photometric, and visual properties similar to OLED panels; however, the differences and similarities between these two technologies have not been systematically compared. A reasonable question would be whether OLEDs are not glary because their light output is insufficient to produce glare or because they are unique in some other way. A recent study showed that, under a fixed background illumination and visual size, both OLED and edge-lit LED panels reached a similar luminance at which both appeared equally glary.³ The goal of this study was to validate the hypothesis that, if the luminance is sufficiently high, both OLED and edge-lit

LED panels can appear equally bright under the same viewing conditions. As part of the study, predictions from different discomfort glare (DG) models were compared to the subjective ratings from human observers.

2 Background

2.1 What is Glare?

In most applications, glare is an undesirable characteristic of a lighting system in a space. Generally, glare is understood to be produced by excessive and uncontrolled brightness in the field of view. Glare from a light source can result in the loss of visibility (i.e., disability glare) or can produce discomfort or even pain (i.e., DG).^{4,5} Disability glare is primarily caused by scattered light inside the eye, resulting in reduced contrast of the retinal image and thus reducing visibility. Disability glare is fairly well understood, and its effects can be estimated if the photometric characteristics of the viewing conditions are known. On the other hand, DG is thought to be more subjective and can vary widely among people due to differences in sensitivity or even their interpretation of the rating scale used to measure it. Several factors are known to influence DG such as the size and intensity of the light source, the amount of light reaching the retina, the viewing geometry, and the luminance and size of the background.^{3–19} DG is thus considered context-dependent, and its estimation is more difficult than for disability glare; nonetheless, different models to estimate subjective ratings of DG have been proposed.^{7–14,17} One of the most widely used rating scales of DG is the de Boer scale, which assigns

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word descriptors to a numerical scale ranging from 1 to 9, where 1 = unbearable, 3 = disturbing, 5 = just acceptable, 7 = satisfactory, and 9 = unnoticeable glare.²⁰ A rating of 5 is generally considered the neutral point where the source is considered just acceptable, and for ratings below 5 the DG moves from disturbing to unbearable.

2.2 Factors that Contribute to Discomfort Glare

Past researchers have explored the factors that contribute to DG.³⁻¹⁹ One of the primary factors contributing to DG is the amount of light that reaches the retina, measured by illuminance at the eye. Bullough et al.⁸ showed that with constant source luminance, by increasing the light source size, the resulting increase in illuminance at the eye resulted in lower numerical ratings using the de Boer scale (less comfortable). Rosenhahn and Lampen¹⁶ reported that for small sources, the human response to DG was highly dependent on illuminance, but, for sources greater than 0.2 deg in visual angle, there seemed to exist a threshold above which luminance started to have an effect on human sensations of DG. This finding was consistent with a subsequent study from Bullough and Sweater-Hickcox,¹⁰ in which it was found that, for a source angular size larger than 0.3 deg, the maximum luminance of the source had a much greater effect on human perceived DG. This means that for a large area lighting panel, not only the illuminance but also the luminance matters. Bullough and Sweater-Hickcox¹⁰ conducted an experiment where subjects looked at three conditions, each with light sources of similar illuminance. In the first and second conditions, the light sources were shielded by a diffuser (maximum luminance: 15,000 cd/m²) or a clear acrylic plate (maximum luminance: 50,000 cd/m²), whereas the third condition involved direct view of the light source (maximum luminance: 1,000,000 cd/m²). The results of this study showed that the condition with the diffuser was rated to have the lowest DG, even though all three conditions had the same measured illuminance at the eye. A similar conclusion was made in the glare assessment of windows.¹⁷ With a nonuniform light source generated to mimic the appearance of a scene seen through a window, Shin et al.¹⁸ found that increases in source luminance increased the perceived DG. In addition, they showed that the mean luminance of the panel had the highest correlation to human perceived DG over the maximum luminance and the minimum luminance of the light source. In those studies, the sizes of the light source were fixed; thus, the increase of luminance also increased the illuminance at the eye. A recent study of Mou et al.³ showed that under a fixed background illumination, when luminance increases, observers gave the same ratings of DG to either an OLED panel or an edge-lit panel. Furthermore, studies have shown that under constant source luminance, when the background illuminance increased, the de Boer rating increased (less glare) due to a reduction in contrast between the glare source and the background.^{6-10,15,19} One study by Osterhaus et al.¹⁵ showed that when a subject was looking at a computer screen with a large glare source behind the monitor, the subject response with the de Boer rating decreased (less comfortable) due to not only the increase in source luminance but also the increase in contrast with the background. Similarly, in a series of experiments, Bullough et al.⁶⁻¹⁰ looked at DG in headlamp and outdoor lighting applications with dim and bright backgrounds and found the highest de Boer ratings for those conditions evaluated against the brighter backgrounds.

3 Methods

3.1 Overview

A psychophysical laboratory experiment was designed to test the hypothesis that, for a given light source size and viewing geometry corresponding to a wall-sconce lighting application, the glare from OLED and edge-lit LED panels would increase with increasing panel luminance. The experiment design also considered the impact of different background lighting conditions on subjective DG. A wall-sconce lighting application was selected as a realistic situation where OLEDs are presently being used.

A $2 \times 5 \times 3$ factorial design was used. The independent variables were two light source types (OLED and edge-lit LED), five light source conditions, and three background lighting conditions. The five light source conditions were characterized by the luminance of the light source as well as the illuminance at the eye for each of those conditions. The three background conditions were selected based on the illuminance at the eye that each background condition produced. The dependent variable was the subjective rating of DG as measured by the de Boer scale. The experimental protocol was approved by Rensselaer Polytechnic Institute's Institutional Review Board (IRB) and explained to the observers with a signed consent form prior to their participation.

3.2 Subjects

Five volunteers (three females and two males, 19- to 40-years old) from the Rensselaer community participated in the experiment. Each observer was tested individually in sessions that lasted no more than 15 min.

3.3 Experimental Setup and Protocol

The setup consisted of one OLED lighting panel and one edge-lit LED lighting panel, a chin rest to control the subjects' viewing location, a white baffle to create a background, and an array of LED strips aimed at the white baffle for generating different background conditions. The setup is shown in Fig. 1.

The five light source conditions were created by changing the input current of the light source to achieve a luminance of 500, 1000, 3000, 5000, or 7000 cd/m². The photometric performance of each of the two source types (OLED, edge-lit LED) has been described by Mou et al.³ The photometric performance of each panel, including correlated color temperature (CCT) and spectrum, is presented in the Appendix. The corresponding illuminances at the eye from each of the five conditions were 50, 100, 300, 500, and 700 lx, respectively. The background lighting condition was created by an array of LED strips with a CCT of 4500 K. The background conditions were 1, 75, or 215 cd/m², and their corresponding illuminances at the eye were 1, 100, or 300 lx. The illuminance uniformity on the background (white baffle in Fig. 1) was measured to be 1.5:1 (average to minimum). The distance from the chin rest to the test light source was set at 30 cm so that the light source subtended a 15-deg field of view. Under these conditions, the background subtended 80 deg.

The experiment was conducted in the Levin Photometry Laboratory located at the Lighting Research Center. Each subject was asked to sit and fix his/her chin at the chin rest at the beginning of the test session. Subjects were instructed to look at

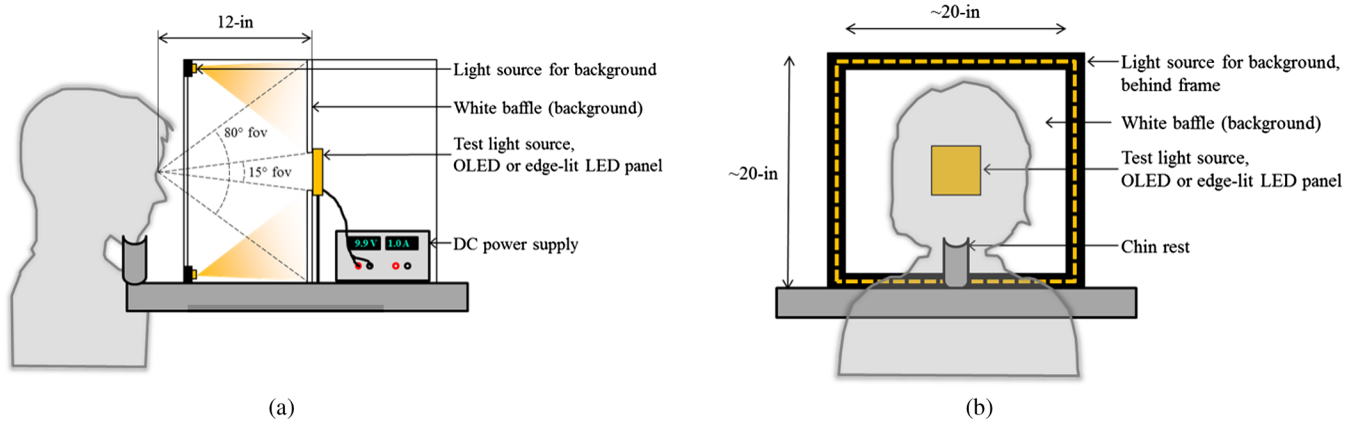


Fig. 1 Illustration of the experimental setup: (a) side view and (b) front view (subject's view).

the test light source and background for 30 s before they were asked to rate the glare from the test light source using the de Boer scale. Subjects were presented with a light source luminance of 1000 cd/m² and a 75 cd/m² background luminance condition for 10 s in between test conditions to clear their memory and avoid dark adaptation. The test conditions were counterbalanced in order.

4 Results

Figure 2 shows the mean de Boer subjective ratings for each of the 15 test conditions (5 light source luminances × 3 background illuminances) from both the OLED and the edge-lit LED panels. As expected, the results show a clear trend of decreasing de Boer ratings (more glare) as light source luminance increases. Similarly, the de Boer ratings decrease (more glare) as the background illuminance decreases. A within-subjects analysis of variance (ANOVA)²¹ was performed to look at different conditions. In the ANOVA, it was found that the two-way interactions (source luminance × background illuminance) were statistically significant ($p < 0.05$) in both the OLED and the edge-lit LED panels. Student's *t*-tests²¹ showed a statistically significant difference ($p < 0.05$) between background illuminances of 1 and 100 lx, 100 and 300 lx, and 1 and 300 lx for a source luminance of 7000 cd/m².

Figure 3 shows a comparison between the mean de Boer subjective ratings for the OLED and the LED edge-lit panels as a

function of source luminance for each background illuminance. No statistically significant differences ($p > 0.05$) were found for any of the possible pairwise comparisons between OLED and edge-lit LED conditions.

To further illustrate these findings, Fig. 4 shows in one plot all of the de Boer subjective ratings given to the OLED panel conditions versus the ratings of the edge-lit LED panel conditions. The ratings given to both light sources showed very good agreement. The slope and the coefficient of determination of the linear correlation are both near unity.

4.1 Performance of Discomfort Glare Models

As OLED (and edge-lit LED) panels evolve and become brighter, it would be very useful to have predictive models that would allow manufacturers and designers to estimate the potential for glare, rather than relying on subjective observations. Several researchers have proposed models to predict human perceived DG, most notably the unified glare rating (UGR),^{11,12} the visual comfort probability (VCP),¹⁴ the outdoor site-lighting performance (OSP) DG model and its extensions (henceforth simply called the OSP model),⁷⁻¹⁰ and a model by Schmidt-Clausen and Bindels.¹⁷ To understand these models' ability to predict subjective ratings of glare, a comparison was conducted between the estimates from two of these models and the results of this study.

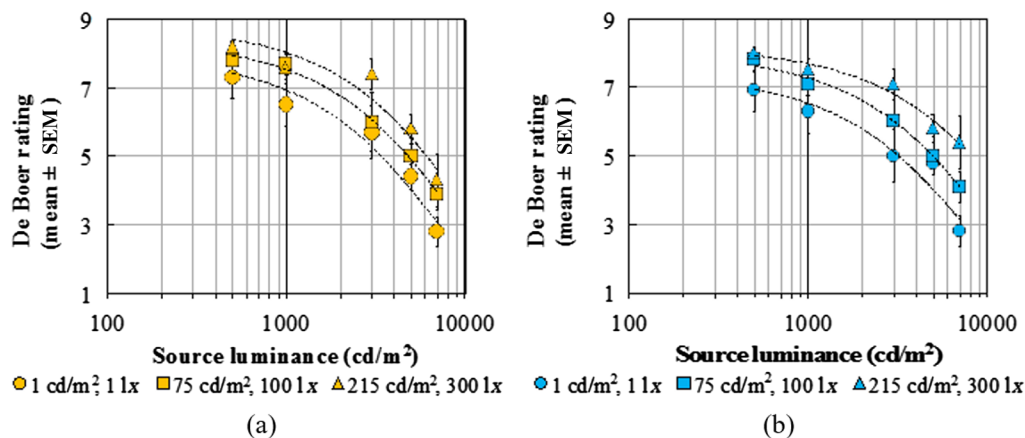


Fig. 2 De Boer ratings (mean ± SEM) as a function of light source luminance for each background luminance and corresponding illuminance at the eye for (a) OLED and (b) edge-lit LED panel conditions.

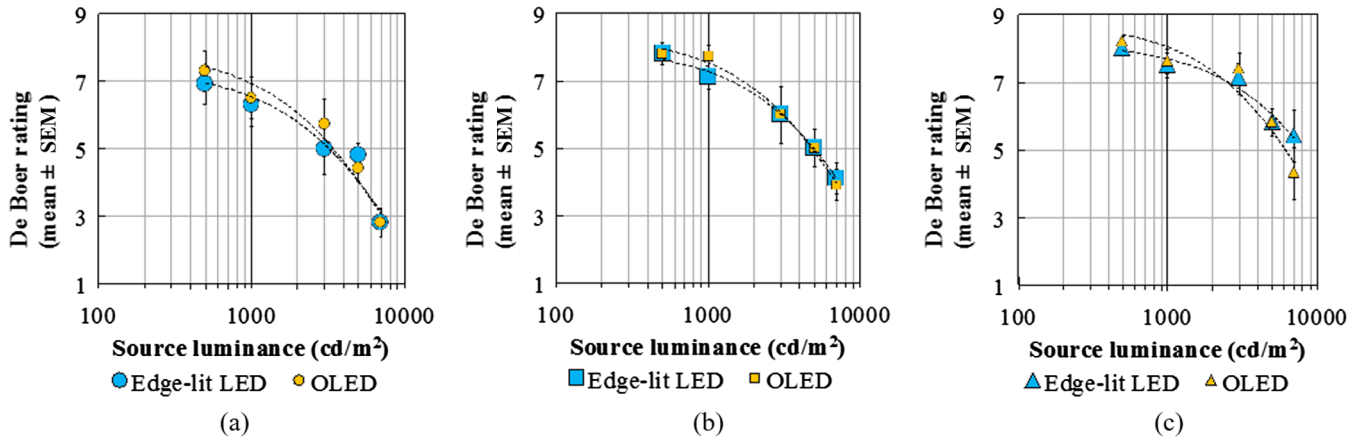


Fig. 3 De Boer ratings (mean \pm SEM) as a function of light source luminance for each background luminance and its corresponding illuminance at the eye of (a) 1 cd/m^2 , 1 lx, (b) 75 cd/m^2 , 100 lx, and (c) 215 cd/m^2 , 300 lx.

For interior lighting conditions, the UGR model has been shown to provide better predictions of subjective responses than the VCP model.²² Moreover, Akashi et al.²³ showed some differences between human subjective responses of DG and the calculated UGR. In parallel, the OSP glare model has been shown to have good correlation with subjective ratings of DG in both outdoor and indoor (albeit simulating outdoor) conditions.⁷⁻⁸ In this study, these two models (UGR and OSP) were used for the prediction analysis.

Figure 5 shows the components of both the UGR and the OSP models, where L is the luminance of the i 'th part of the glare light source in the direction of the eye, E_L is the illuminance at the eye from the light source, E_S is the illuminance at the eye from the background (excluding the glare source), E_A is the illuminance at the eye from the ambient lighting in the location, L_b is the luminance of the background in the direction of the eye, ω is the solid angle (in steradian) of the i 'th part of the glare source, and p is the position index of the i 'th part of the glare light source (see Chapter 9 of Ref. 4 for details).

In the OSP model,⁷⁻¹⁰ the authors modeled DG [Eq. (1)] based on illuminance quantities (E_L , E_S , and E_A). The coefficients, $a = 1.0$, $b = 0.6$, and $c = 0.5$, were determined empirically⁷

$$DG = a \log(E_L + E_S) + b \log(E_L/E_S) - c \log(E_A). \quad (1)$$

DG values can be converted to a numerical value in the de Boer rating scale using Eq. (2) if the size of the light source subtends an angle equal to or greater than 0.3 deg ¹⁰

$$DB = 6.6 - 6.4 \log DG + 1.4 \log(50,000/L). \quad (2)$$

A similar approach was followed for the UGR calculation, and a UGR equation [Eq. (3)] was selected that was suitable for the range of source sizes within 0.0003 to 0.1 sr ¹²

$$UGR = 8 \cdot \log \left[\frac{0.25}{L_b} \sum_{i=1}^n \frac{L_i^2 \omega_i}{P_i^2} \right]. \quad (3)$$

The summation term in the UGR system comes from the cases when multiple glare light sources are present. In this study, only one glare source is investigated; thus, $n = 1$.

Given that the UGR model provides a scale in the range from 10 to 30, it was necessary to find a way to correlate these values with a corresponding value in the de Boer scale. The correlation between UGR and de Boer values was based on the results by Tyukhova,¹⁹ who collected responses of subjective DG and correlated the observers' responses with the de Boer scale values estimated using the OSP model and the UGR values for a series of known conditions. Using data of Tyukhova, it was possible to estimate a linear correlation [Eq. (4); $R^2 = 0.93$] between the de Boer ratings and UGR values

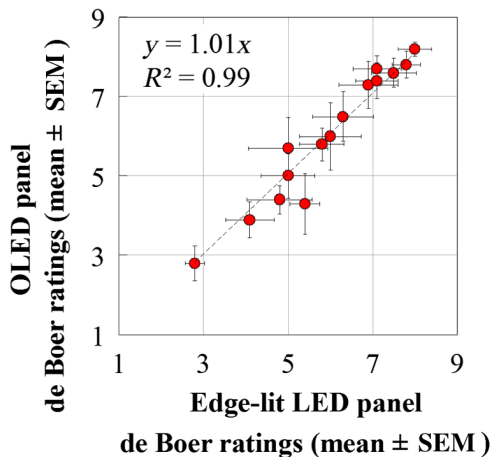


Fig. 4 Goodness of fit (R^2) between the mean de Boer ratings of all tested conditions for OLED and edge-lit LED panels.

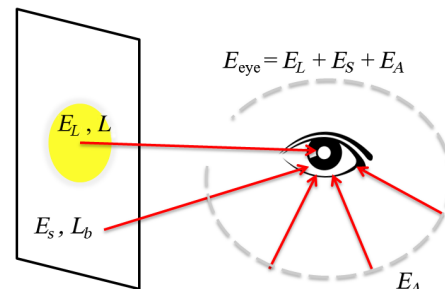


Fig. 5 Illustration of the lighting parameters that contribute to DG in the UGR and OSP models.⁷⁻¹²

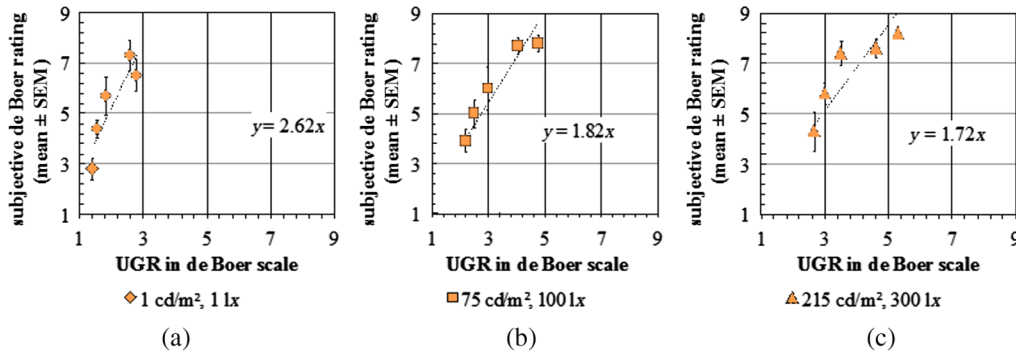


Fig. 6 Observed versus predicted UGR values in de Boer ratings for each background condition with OLED panel data. Background conditions are (a) 1 cd/m², 1 lx; (b) 75 cd/m², 100 lx; and (c) 215 cd/m², 300 lx.

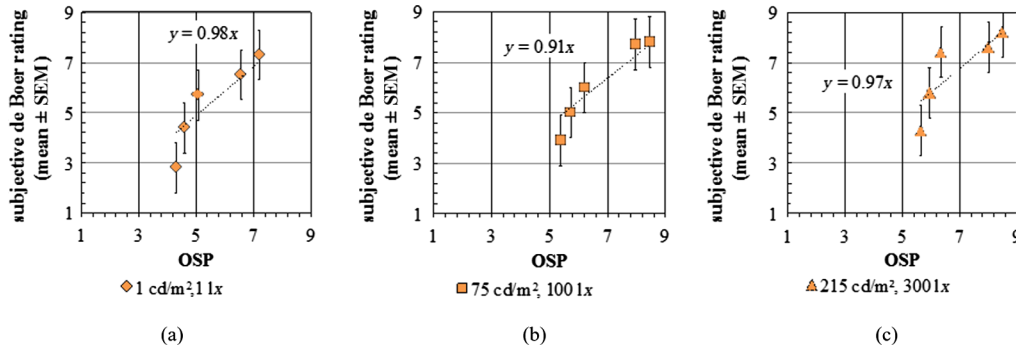


Fig. 7 Observed versus predicted OSP values in de Boer ratings for each background condition with OLED panel data. Background conditions are (a) 1 cd/m², 1 lx; (b) 75 cd/m², 100 lx; and (c) 215 cd/m², 300 lx.

$$DB_{UGR} = -0.15 UGR + 7.58. \tag{4}$$

Figures 6 and 7 show the results of the comparisons between the observed and the predicted de Boer ratings. Both models showed similar trends: as the luminance of the light source increased, the predicted de Boer ratings decreased (more glare). Both models showed a high goodness of fit ($R^2 > 0.97$). However, the UGR predictions overestimated perceptions of glare by an average of two points in the de Boer scale. The OSP model [Eq. (2)] showed much closer predictions of the de Boer ratings. While it is possible that the best fitting functions relating the pairs of values in Figs. 6 and 7 are not truly linear, possibly because of range effects associated with the specific

conditions in the experiment,²⁴ the analysis still has utility as a comparison between different models. The slopes in Fig. 6 differ substantially from unity, whereas those in Fig. 7 are much closer to unity.

Moreover, in the OSP model,¹⁰ the coefficient 1.4 was empirically determined for conditions based on the viewing of a car’s headlamp or an outdoor luminaire, for which the background contrast is much greater than might be expected in indoor conditions. Similarly, the coefficient 50,000 in Eq. (2) was determined based on the average luminance of the light sources used in the experiments from which Eq. (1) was derived.⁷⁻¹⁰ Thus, to make the model applicable to this study’s lighting conditions by following a similar procedure, new coefficients (2.8 and 7000)

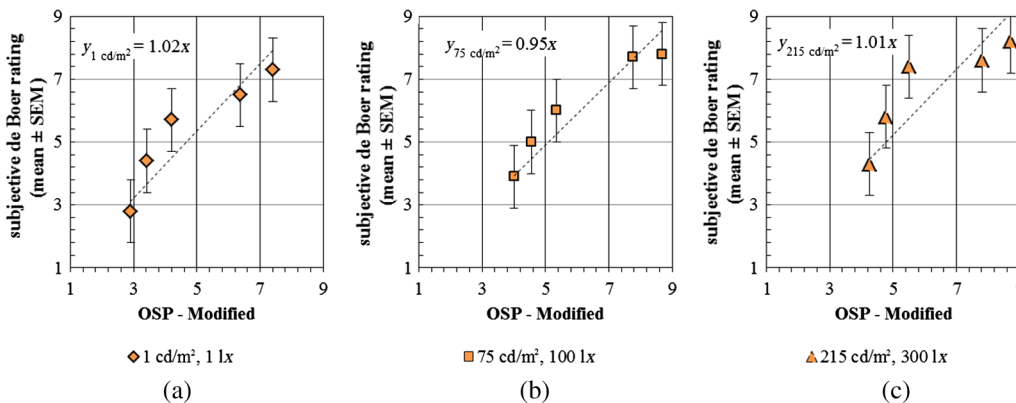


Fig. 8 Observed versus predicted de Boer ratings (modified OSP model) for each background condition with OLED panel data. Background conditions are (a) 1 cd/m², 1 lx; (b) 75 cd/m², 100 lx; and (c) 215 cd/m², 300 lx.

were determined, as shown in Eq. (5).¹⁰ Figure 8 shows the correlations between the observed and the predicted de Boer ratings using the modified OSP model

$$DB_{\text{modified}} = 6.6 - 6.4 \log DG + 2.9 \log(7000/L). \quad (5)$$

For practical application, the original OSP model provides a good estimation of human observed DG. When the OSP model was fitted with a 95% confidence interval, it showed no statistically significant difference with the modified OSP model. An average observed value of 5 in the de Boer rating scale for a given lighting condition will be equivalent to a predicted value of 4 to 6 in the de Boer scale, which is within the variations due to individual differences. The benefit of further optimizing the OSP model is not to merely show a closer estimation but to better interpret the model variables with the actual context of the lighting environment. With the new determined coefficients, the OSP model modified or an indoor application scenario reveals that DG is dependent on both the illuminances at the eye and the luminance of the light source.

5 Discussion and Conclusions

This preliminary study evaluated perceptions of DG from two commercially available OLED and edge-lit LED panels and found no statistical difference in DG between the two sources when matched for their illuminance and luminance characteristics. Furthermore, the results of this study show that, under realistic conditions involving a wall-sconce application, panels with a luminance of ~5000 cd/m² or greater resulted in glare conditions that, on average, would be described as unacceptable or even disturbing according to the de Boer rating scale. This finding is consistent with the conclusion from the study by Shin et al.¹⁸

Predictions from the UGR and OSP models of DG were compared with the observations in this study. For the conditions used in this study, the OSP model showed a better correlation with the observed values than the UGR model. Although the UGR model considers the background luminance and the source luminance, it disregards the illuminance effect when the glare source creates a solid angle that is within 0.0003 to 0.1 sr. In contrast, the OSP and modified OSP models consider the contributions to illuminance at the eye from both the glare source and ambient lighting. The modified OSP model showed even better correlations with the observed values than the OSP model, and the new calculated coefficients helped in explaining why the model more closely predicts the subjective response.

In Table 1, two practical application scenarios are presented: a museum lighting condition and an office lighting condition. In the museum context, it is assumed that the space requires higher contrast for a strong visual effect.⁵ Thus, the ambient illuminance is often low. With the illuminance at the eye from ambient lighting controlled at 1 lx, we can use the modified OSP model to estimate the limit of source luminance when it becomes glaring (a de Boer rating of 5—just acceptable was used as the threshold limit). This model predicts that the source luminance should be controlled to a limit of 4150 cd/m² to avoid unacceptable DG when a lighting panel is used in a wall-sconce application (perpendicular view). A similar procedure can be applied to identify the maximum acceptable (for glare) panel luminance in the office lighting condition.

The examples in Table 1 and Fig. 9 show how, by measuring the appropriate lighting quantities, the modified OSP model can be used to estimate reasonably accurate predictions of human

Table 1 Predicted lighting characteristics for different applications to avoid unacceptable DG.

Condition	Application	Background luminance (cd/m ²), Illuminance at the eye from background (lx)	Light source luminance limit (cd/m ²)
A	Museum	1, 1	4150
B	Office	75, 100	5780

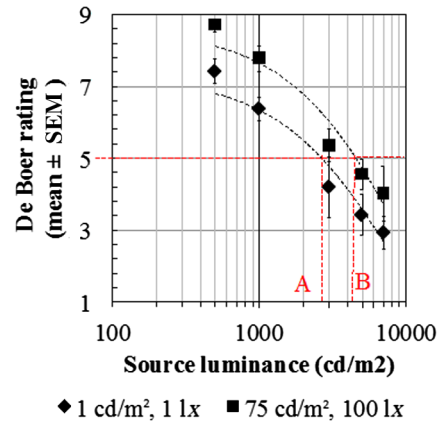


Fig. 9 The modified OSP model predictions at two illuminance conditions.

sensations of DG and, thus, help manufacturers and lighting designers to create a visually comfortable space.

Appendix: Photometric Performance of the OLED and Edge-Lit LED Panels

One edge-lit LED panel and one OLED panel of similar size were selected for the study. Both were commercially available products. The edge-lit LED panel (126.0 mm × 126.0 mm lit area) operates at 12 V_{dc} with rated current at 500 mA, and the OLED panel (102.4 mm × 102.4 mm lit area) operates at 24 V_{dc} with rated current at 368 mA. The CCT and spectrum as a function of input current were measured in a calibrated integrating sphere. The results of the photometric characterizations are shown in Fig. 10.

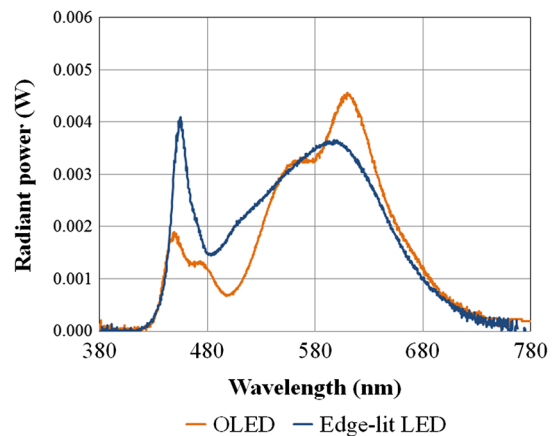


Fig. 10 Spectral power distributions of the edge-lit LED and OLED panels used in this study.

Table 2 Photometric performance of the edge-lit LED and OLED panels used in this study.

	Input current (A)	Luminous flux (lm)	Average luminance (cd/m ²)	Chromaticity (x, y)	Efficacy (lm/W)	CCT (K)
Edge-lit LED panel	0.35	286.2	5000	x = 0.3812, y = 0.3801	86.4	3979
OLED panel	0.35	278.0	6500	x = 0.4410, y = 0.4000	39.0	2900

The edge-lit LED and OLED panels selected for the study have very similar light output under the same input current, but the edge-lit panel is more efficacious than the OLED panel, as shown in Table 2. The measured CCTs were about 3000 K for the OLED panel and about 4000 K for the edge-lit LED panel. Panels with more similar CCTs were not available commercially at the time of the study.

Disclosures

No conflicts of interest, financial or otherwise, are declared by the authors.

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