

Defining the visual adaptation field for mesopic photometry: How does the high-luminance source affect peripheral adaptation?

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Abstract

CIE 191:2010 recommends the mesopic photometry system, in which the luminous efficiency function is determined from the adaptation luminance. However, it cannot be implemented because the adaptation field to determine the adaptation luminance is not defined. Surrounding luminance effect is a key factor to define the adaptation field. Vision experiments have been conducted to measure the surrounding luminance effect on peripheral adaptation state with a point source at varied intensities placed at different position. The results reveal that the effect can be described as veiling luminance and that the magnitude of the effect is larger than that of the foveal veiling luminance. A model for the peripheral veiling luminance proposed by Stiles and Crawford in 1937 shows the best prediction for the surrounding luminance effect.

1 Introduction

The International Commission on Illumination (CIE) has recommended a mesopic photometry system based on peripheral performance of tasks, such as detection, reaction time and recognition.¹ It takes into account the Purkinje effect, which is the shift of the spectral luminous efficiency function to shorter wavelengths at lower light levels. The mesopic photometry system properly evaluates potential advantages in luminous efficacy of light sources that are rich in short wavelength components, such as light-emitting diodes (LEDs) over the conventional light sources for outdoor lighting such as high-pressure sodium lamps (HPS). Thus, the CIE mesopic photometry system is expected to enable the lighting industry to develop and design more energy efficient and/or visually effective lighting for outdoor applications.

However, there are some remaining issues before the mesopic photometry system can be implemented in real applications, which are under discussion in CIE JTC-1. The committee is developing a CIE technical report for implementing CIE 191 mesopic photometry system to be applied to real applications. One of the important issues is to define the adaptation field,^{2,3} which is used to determine the adaptation state for lighting scenes. Since the mesopic spectral luminous efficiency function changes its shape depending on the adaptation state of observers, the adaptation state for a given lighting scene has to be determined from luminance distribution in the adaptation field. Once the adaptation state has been determined for the lighting scene, photometric quantities can be measured with a mesopic spectral luminous

efficiency function corresponding to the adaptation state. However, there is no definition of the adaptation field at present.

We previously conducted an experimental study to address this issue.⁴ It showed that the adaptation state depends primarily on the local luminance of the task point, but is also slightly affected by the surrounding luminance. The study suggested that glare sources in lighting scenes may affect the adaptation state significantly. However, our previous experiments were not sufficient to determine the magnitude of the effects of glare sources on the adaptation state accurately.

To define the adaptation field for mesopic photometry, it is further necessary to determine the effects of glare sources, such as direct lights from road lighting luminaires, on the adaptation state in mesopic photometry. To provide such data for the effects of glare sources, we conducted vision experiments testing the detection of a target in peripheral vision using an LCD display, with a white LED point source (simulating a glare source) set at varied intensities and angles from the target. The experimental procedures and the results are presented.

2 Existing models and knowledge on adaptation luminance

The CIE system of mesopic photometry¹ defines the mesopic spectral luminous efficiency function $V_{\text{mes}}(\lambda)$ by the equation:

$$V_{\text{mes}}(\lambda) = \frac{1}{M(\lambda)} \{mV(\lambda) + (1 - m)V'(\lambda)\} \quad \text{for } 0 \leq m \leq 1 \quad (1)$$

where $V(\lambda)$ is the photopic luminous efficiency function, $V(\lambda)$ is the scotopic luminous efficiency function and $M(m)$ is a normalization function to attain the maximum value of $V_{\text{mes}}(\lambda)$ always to one. The m is a coefficient that represents the visual adaptation state, which causes changes of the shape of $V_{\text{mes}}(\lambda)$. To determine the value of m , the photopic and scotopic luminances of an adaptation field are required. However, the size and shape of the adaptation field, or any weighting function for the effect of surrounding luminance, have not been defined.³ Note that the CIE mesopic photometry system is based on the peripheral task performance.^{5,6,7,8,9}

A question to be considered for the definition of the adaptation field is how the surrounding luminance distribution affects the adaptation state for a peripheral point in the observer's visual field. There are two factors for the surrounding luminance effects on the adaptation state. The first factor is the surrounding luminance distribution itself. Stray light within the eye and lateral neural interactions are candidate mechanisms for this factor. The second factor is the movement of line of sight, which depends on the lighting applications.^{2,10} This factor broadens the adaptation field determined by the first factor. It is first necessary to determine the first factor.

For the foveal adaptation, it is shown that the surrounding luminance effect on the adaptation state when the line of sight is fixed can be described by the formula of veiling luminance in the studies by Narisada et. al.^{11,12} These studies focused on the effects by glare sources on the foveal adaptation state rather than the masking effect by glare sources, which reduces luminance contrast. In these studies, the adaptation luminance L_a can be

predicted by the equation:

$$L_a = L_{\text{local}} + L_{\text{veil}} \quad (2)$$

where L_{local} is the local luminance at which the fovea looks, L_{veil} is the veiling luminance caused by the surrounding luminance distribution. The adaptation luminance L_a in Equation 2, which includes the surrounding luminance effect, is hereinafter referred to as “effective adaptation luminance”. L_{veil} can be calculated by using models for foveal veiling luminance, such as the Stiles-Holladay disability glare formula¹³ or the CIE General Disability Glare Equation.¹⁴ Based on the Stiles-Holladay formula,^{15,16,17,18} L_{veil} is obtained by

$$L_{\text{veil}} = \frac{10}{\theta^2} E \quad (3)$$

where E is the vertical illuminance at the observer’s eye due to a glare source, and θ is the visual angle (in degrees) between the glare source and the line of sight. According to studies taking into account age, eye pigment, and the data for ranges of angle near fovea,^{19,20,21} CIE has developed and recommended General Disability Glare Equation as:

$$L_{\text{veil}} = \left\{ \frac{10}{\theta^3} + \left[\frac{5}{\theta^2} + \frac{0.1p}{\theta} \right] \cdot \left[1 + \left(\frac{A}{62.5} \right)^4 \right] + 0.0025p \right\} E \quad (4)$$

where A is the age of the observer in year, p is the eye pigment factor, which ranges from 0 for black eyes to 1.2 for very light-blue eyes. The experimental data for these models are also for foveal vision.

On the other hand, Stiles and Crawford²² proposed a model for the veiling luminance on the peripheral task, based on a number of vision experiments, as:

$$L_{\text{veil}} = \frac{16}{\theta^2} E_n \quad (5)$$

where E_n is the normal illuminance (on a plane perpendicular to the direction from the source) at the observer's eye due to a glare source, and θ is visual angle (in degrees) between the glare source and a task point where the veiling luminance is caused. A value of veiling luminance predicted by the model is more than 1.6 times the value predicted by the Stiles-Holladay equation. However, these formulae are based on data in both photopic vision and mesopic vision, and it is not clear whether these models can predict the surrounding luminance effect on the adaptation state particularly in mesopic vision.

It should be noted that the three models for the veiling luminance are based on experiments in which subjects adapted to a stimulus with a glare source and performed detection tasks with the same stimulus, thus mixing the effects of the adaptation state changes and the masking effect caused by the luminance increment on the task point during the detection tasks.

Narisada et al. showed that the adaptation state changes alone also can be

modeled as Stiles-Holladay formula for fovea, but it has not been shown for Stiles-Crawford formula for peripheral vision.

Our previous experiments⁴ showed that the adaptation state for peripheral detection task in mesopic range depends primarily on the local luminance of the task point, but is also slightly affected by the surrounding luminance. These experiments also suggested that the surrounding luminance effect could be larger than the effect predicted by the foveal veiling luminance models. However, the veiling luminance levels in the experiments were too low to evaluate the magnitude of the surrounding luminance effect accurately. Furthermore, the experiment results do not give any information regarding relationship between the surrounding luminance effect and the position (angle) and the intensity of the surrounding source (glare source), because the experiments investigated only the effect caused by an area light source that has a given luminance level.

Even though the previous experiments suggest that the surrounding luminance can be nearly neglected for uniform surrounding luminance distributions, it is still important to characterize the effect of surrounding luminance for the case of higher luminance point-like sources (glare sources) in relation to the position of the source. This is necessary because the outdoor lighting scenes often have high-luminance stimuli, such as direct light from luminaires and/or head lights of oncoming cars, which may affect the adaptation state significantly. However, as described above, it is not clear that the existing veiling luminance models, for both foveal and peripheral vision, can predict the surrounding luminance effect on the peripheral

adaptation state.

Therefore, we conducted vision experiments to characterize the effect of surrounding luminance from high-luminance point sources on the adaptation state for a peripheral task point.

3 Experimental Method

The principles of these experiments are the same as those in previous experiments by authors.⁴ The adaptation state of the subject is estimated by measuring the luminance contrast detection thresholds. When the subject adapts to a luminance distribution, while factors other than the adaptation are fixed, the threshold can represent the adaptation state corresponding to the luminance distribution.¹¹

Two experiments were conducted. The first experiment measured detection thresholds when the subject was adapted to stimuli that have a high-luminance point source, with its luminance and the position varied. This is hereinafter referred to as “point source experiment.” The second experiment characterized the effect of uniform adaptation stimuli, of varied luminance levels, on luminance contrast detection threshold. This experiment is referred to as “uniform experiment.”

3.1 Set-up

The experimental set-up is shown in Figure 1.

A computer-controlled liquid crystal display (LCD), the screen of which

was covered with neutral density (ND) filter panels, was employed to present the target and its background. The display has 10 bit control (1024 levels) of pixel luminance. Prior to every experimental session, the LCD was warmed up to ensure that stabilization is reached. The luminance at the target position on the LCD screen was calibrated by using a calibrated luminance meter placed at the subject's eye position. The target and the background presented by the LCD were white. The correlated color temperature (CCT) and scotopic/photopic (S/P) ratio of those were 4690 K and 2.21, respectively. The expanded uncertainties ($k = 2$) of measured luminance, CCT, and SP ratio of the display were 2.0 %, 60 K, and 0.02, respectively. A white circular LED unit was used as a high-luminance point source. It consists of a chip-on-board phosphor LED module with a diameter of 20 mm, placed in front of the LED module, producing fairly uniform luminance distribution over the light emitting surface and near-Lambertian angular intensity distribution. The LED unit was placed in front of the LCD at 4 cm from the LCD screen. Care was taken so that no light from the LED fell on the LCD screen. The LED was driven with a direct current (DC) power supply controlled by the computer, and dimmed by changing the current level. This dimming method caused small chromaticity change depending on the current level. However, through the current range employed in the experiment, the change of chromaticity, when changing the luminance level, was less than 0.002 in u' , v' coordinate, which was not considered significant. The temporal luminance change, which is caused by the change of temperature of LED, was less than 1 % in three minutes. Because it is

difficult to measure the luminance of the LED with good reproducibility, the vertical illuminance from the LED at the subject's eye position was measured by using an illuminance meter, which was calibrated with a spectroradiometer (calibrated against NIST spectral irradiance scale) measuring the particular LED used in the experiment. In the later part of this paper, the luminous output of the LED is described in the vertical illuminance at observer's eye position. The CCT and S/P ratio of the LED, measured with the spectroradiometer, were 6120K and 2.28. The expanded uncertainties ($k=2$) of measured illuminance, CCT, and SP ratio of the LED were 2.0 %, 80 K, and 0.02, respectively. This LED was chosen because its S/P ratio was nearly equal to that of the LCD.

A subject was positioned at a viewing distance of 65 cm and fixed his/her head on a chin rest during adaptation and experimental trials. At this distance, the LCD screen subtended a visual angle of $49^\circ \times 29^\circ$, and the diameter of the LED was 1.8° of visual angles. Subjects responded whether he/she saw a target on the LCD by clicking a mouse (left/right click). The response data was automatically corrected with the computer. All experiments were conducted in a darkroom.

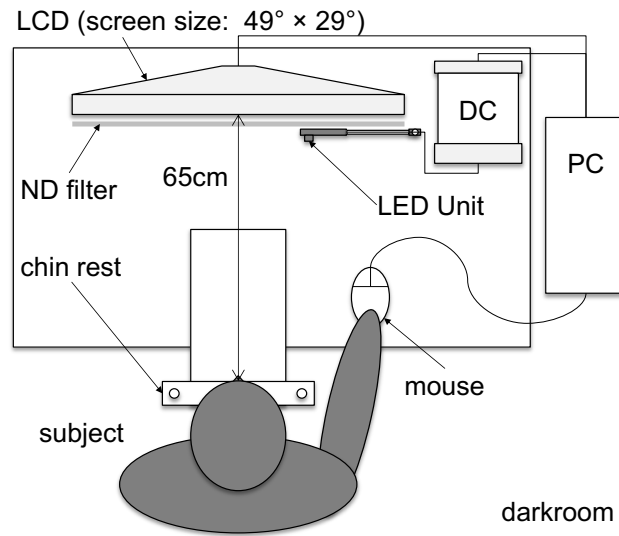


Figure1 Depiction of the experimental set-up

3.2 Procedures and stimuli

3.2.1 Point Source Experiment

The patterns employed in the point source experiment are shown in Figure 2. In this paper, “pattern” means luminance distribution consisting of the LCD and the LED, to which the subject adapted to or on which the subject performed the detection tasks. In Figure 2, the top row shows the adaptation patterns, to which the subject adapted; and bottom row shows the task patterns, on which the subject performed the tasks. For all patterns, the bottom half of the LCD screen was uniformly set at the background luminance shown in the figure. These patterns represented rough simulations of road lighting scenes at night time, which has dark sky and lit road surface. The luminance of the illuminated area for the adaptation pattern is referred to as “adaptation background luminance,” and that for

the task pattern will be referred to as “task background luminance.” Each adaptation pattern and task pattern at a condition were presented sequentially so that the LED source was turned off during the task. This sequential pattern presentation was employed to remove the masking effect by the point source on the detection thresholds during the tasks, because the point source was absent in the task patterns. It enabled the detection threshold to represent just the adaptation state.¹¹ The conditions in Figure 2 can be separated into point source conditions (three conditions on left side) and reference conditions (two conditions on right side.)

A fixation point was shown as a small cross on the screen, and was positioned at the center of the screen during the time the task pattern was presented. The target to be detected by the subject always appeared in the same position, which was lower right of the fixation point. The visual angle between the fixation point and the target was 10°. The diameter of the target was 1°. The target luminance was varied between trials but was always lower than the task background luminance. While the adaptation pattern was presented (i.e., during the time the subject was adapted to it), the fixation point (the cross on the screen) was moved around in a 2° × 5° oval area centered at the center of the screen every two seconds so that the point source did not excessively stimulate a fixed point on the subject’s retina. This procedure was taken for consideration of photobiological safety of the subject, but also it simulates the eye movement in real applications..

The position of the point source and the vertical illuminance from the source for the adaptation pattern varied between the point source conditions.

Positions of the point source were at 7°, 15°, and 30° above the target. The vertical illuminance levels measured at the position of the subject's eye were 0.3 lx, 0.7 lx, 2.2 lx, and 5.4 lx. Thus, the total number of the point source conditions was twelve. The adaptation background luminance was constant at 0.2 cd/m² for all of the point source conditions. For the reference conditions, there was no point source and the adaptation background luminances were 0.2 cd/m² and 2.0 cd/m². The task background luminance was 0.2 cd/m² for all conditions, including the point source conditions and the reference conditions. These luminance levels were chosen considering the CIE road lighting recommendation.²³

The task of the subject was to indicate whether or not the target was seen on each experimental trial. At the beginning of every experimental condition, the subject adapted to the adaptation pattern for five minutes. The task pattern was then presented for 0.6 s. In the middle of the task pattern presentation, the target appeared for 0.2 s. Following the task pattern presentation, the adaptation pattern was presented again to maintain constant adaptation state. Five seconds after the subject completed each trial, the task pattern was presented again and next trial began with different target luminance. The tasks were repeated until the number of the tasks reached enough to determine a luminance contrast detection threshold, according to the random-staircase method.

For the point source experiment at each point source position, an experimental session consisted of two reference conditions and four point source conditions of different source intensities. Each subject performed

three such sessions for three point source positions. The reference conditions were included in each of three sessions, thus, repeated three times per subject. The sequence of the conditions was randomized, except for the reference condition with the adaptation background luminance of 2.0 cd/m², which was always conducted third. The order of the 2.0 cd/m² reference condition was fixed at the middle of the session so that the result would be used to cancel the inter-session deviation of results for other conditions.

Before an experimental session, the subject adapted to a uniform LCD screen, the luminance of which was 0.2 cd/m², for more than five minutes.

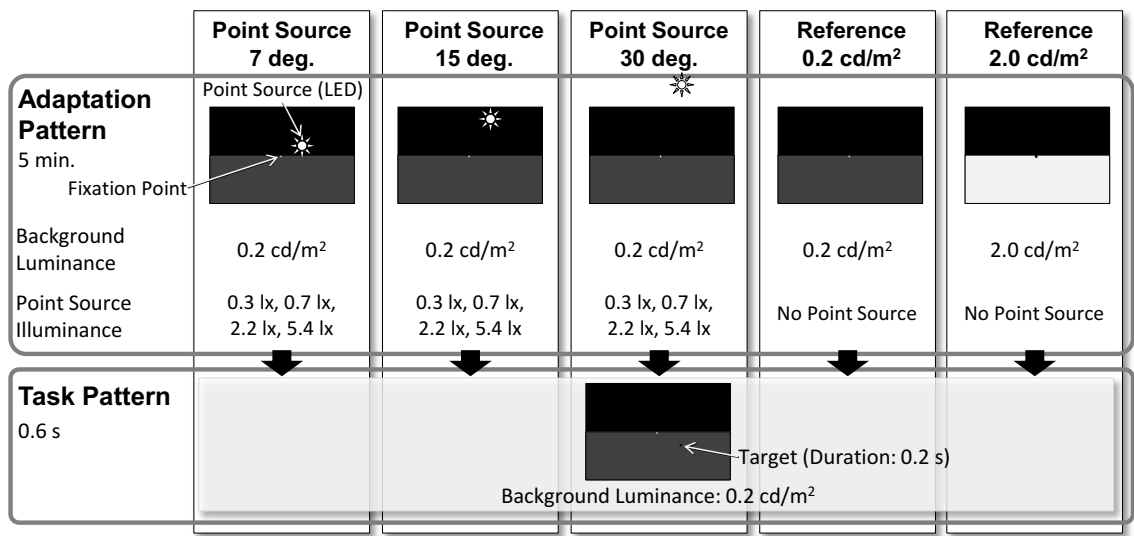


Figure 2 Adaptation patterns and task patterns used for the point source experiment. The top row shows the adaptation patterns, and the bottom row shows the task patterns, for each condition

3.2.2 Uniform Experiment

The second experiment was conducted to determine the relationship between the detection threshold and the adaptation background luminance for the reference conditions (with no point source) in greater details.

The patterns used in the uniform experiment are illustrated in Figure 3. As with Figure 2, the top row shows the adaptation patterns and bottom row shows the task pattern. In this experiment, no conditions had the point source, and the adaptation background luminance was varied gradually between conditions. Nine levels of the adaptation background luminance from 0.2 cd/m^2 to 2.5 cd/m^2 were used. The task patterns, the target, and the fixation point were the same as those for the point source experiment. The fixation point during adaptation was moved around though there was no LED source, to make the experimental conditions the same as point source experiment.

The procedure of the uniform experiment was also the same as the point source experiment. Since there were many conditions, and since each condition was repeated four to six times, the experiments were conducted for four conditions as a session, and the whole experiment was conducted in 13 separate sessions.

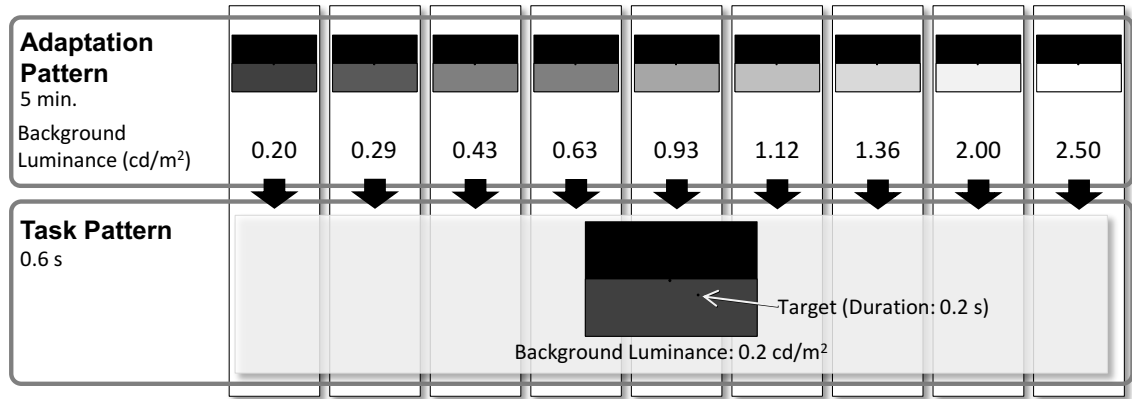


Figure 3 Adaptation patterns and task patterns used for the uniform experiment

3.3 Subjects

Seven subjects with normal vision participated in the point source experiments. Their ages were 32 to 68 years. Four of them were younger than 40 years, one was younger than 50 years, and the others were older than 60 years. Three of them had dark brown eyes, another three had brown eyes, and one of them had light-brown eyes.

The uniform experiment was conducted with a well-trained subject, one of the seven subjects used for the point source experiments.

4 Results

4.1 Point Source Experiment

The mean luminance contrast detection thresholds of all subjects are shown in Figures 4 to 6, for the point source position of 7°, 15°, and 30°,

respectively. These figures show luminance contrast detection threshold C_{th} (ordinate) as a function of the point source illuminance (abscissa). The luminance contrast detection threshold C_{th} was calculated as:

$$C_{th} = \frac{L_b - L_t}{L_b} \quad (6)$$

where L_b is the task background luminance and L_t is the target luminance at the threshold. For descriptive purposes, results of the reference conditions without the point source were plotted at left end of the graph (0 lx of the point source illuminance) with square and triangle symbols. The error bars are the standard deviations of the mean.

The results show that higher point source illuminances basically cause higher detection thresholds, which means lower visual performance. The steeper gradient for closer point source (Fig. 4) shows that the effect of the intensity of the source is higher than at farther angles.

Additionally, the relationship between the results of two reference conditions (shown at the horizontal axis position of 0 lx) suggests that higher effective adaptation luminances cause higher detection thresholds. Because the point source is absent in both conditions, the difference between them is only the adaptation background luminance, which indubitably correlates with the effective adaptation luminance at the task point. If it is assumed that the surrounding luminance effect can be neglected for the reference conditions, the effective adaptation luminances for the reference conditions are nearly equal to the adaptation background luminance.

These results clearly suggest that the presence of the point source increases effective adaptation luminance at the task point. For example, in Figure 4, the detection threshold at the point source illuminance of 5.4 lx, (at the adaptation background luminance of 0.2 cd/m²) is very close to that for the reference condition at the adaptation background luminance of 2.0 cd/m² (shown as the square symbol plotted at 0 lx position). In this case, the effective adaptation luminance of the 5.4 lx point source condition can be estimated to be close to 2.0 cd/m². Further analysis on this point is discussed in section 5.

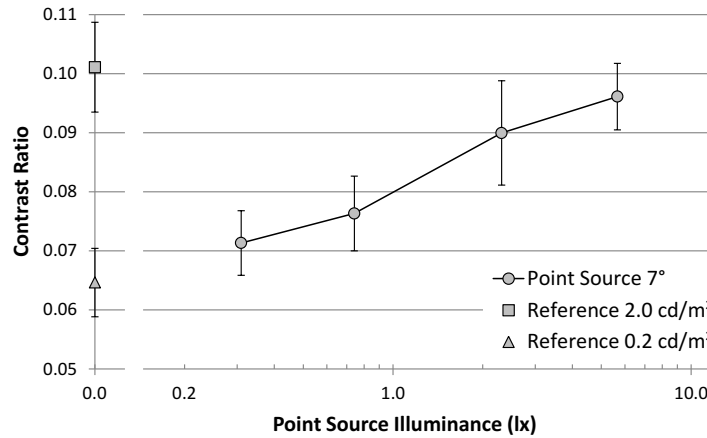


Figure 4 The mean luminance contrast detection thresholds for all subjects for the point source position of 7° in the point source experiment

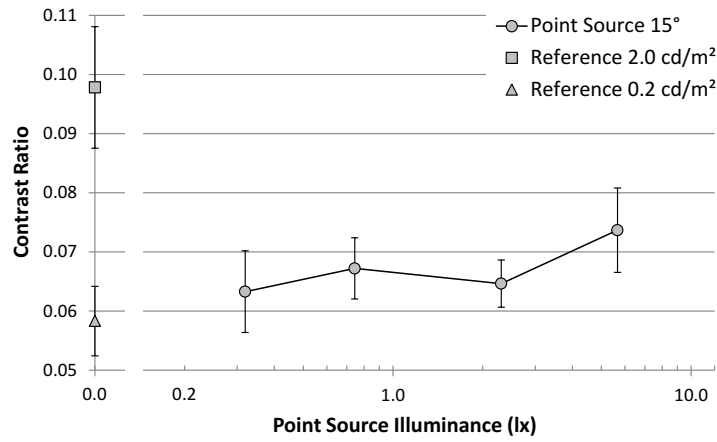


Figure 5 The mean luminance contrast detection thresholds for all subjects for the point source position of 15° in the point source experiment

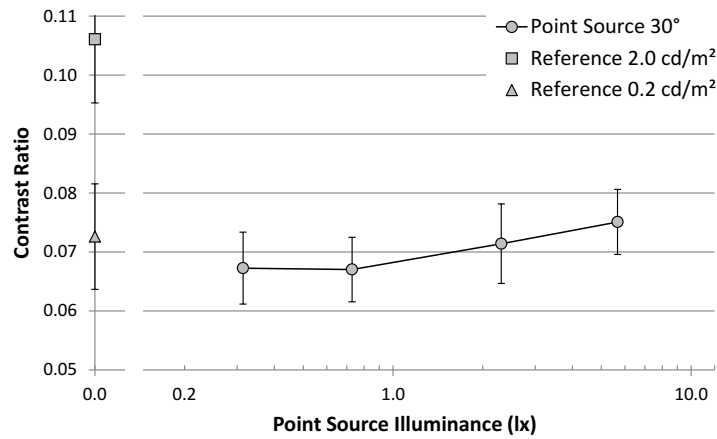


Figure 6 The mean luminance contrast detection thresholds for all subjects for the point source position of 30° in the point source experiment

4.2 Uniform Experiment

The results of the uniform experiment are shown in Figure 7. This figure shows luminance contrast detection threshold (ordinate) as a function of the adaptation background luminance (abscissa). Each point represents the

mean of repeated trials with one subject. The numbers of trials are nine for the adaptation background luminance of 0.2 cd/m², four to six for the other luminance levels. The error bars shows one standard deviation of the mean.

Even though the data has some variation, the trend clearly shows that the detection threshold is linear to the logarithm of the adaptation background luminance. The solid line in Figure 7 is a regression line with an equation:

$$C_{th} = a \log_{10} L_{local} + b \quad (7)$$

where L_{local} is the adaptation background luminance in this case, a and b are regression coefficients. The regression line shows good agreement with experiment results. This tendency is also consistent with our previous experiment result by eleven subjects.⁴

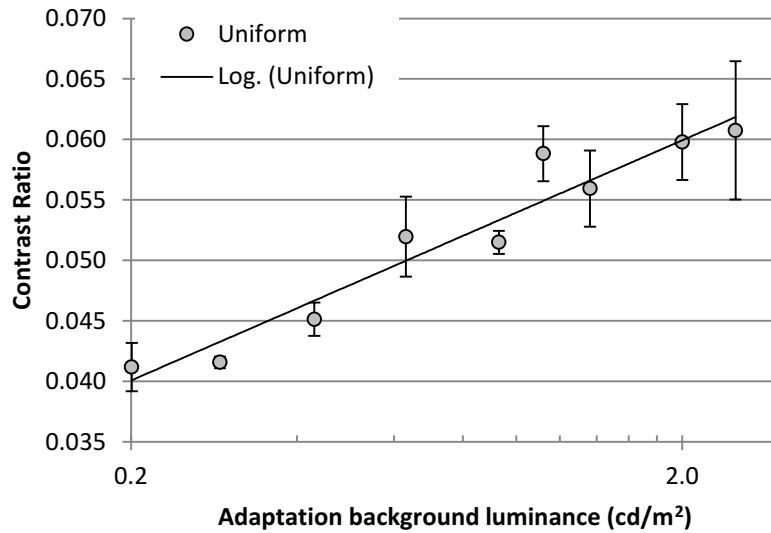


Figure 7 The mean luminance contrast detection thresholds for repeated trials with one subject in the uniform experiment

5 Discussion and analyses

Even though the point source experiment result shows a tendency that the point source increase the effective adaptation luminance, the experiment results give only detection thresholds, and do not indicate the effective adaptation luminance for each condition directly. However, by using function in Equation 7, the effective adaptation luminance for the point source experiment results can be determined from the detection thresholds in Figure 4 to 6. The steps are: first, determine the coefficients a and b in Equation 7 by substituting the reference condition results (two sets of the adaptation background luminance and the detection threshold); then, calculate the effective adaptation luminance for each condition, by substituting the detection threshold to the equation determined in previous step. This calculation removes the inter-session deviation, which appears in the variation of the reference condition results among Figure 4, 5, and 6.

To compare with the experiment results, three models for the effective adaptation luminance were also calculated:

(1) $L_a = L_{\text{local}} + L_{\text{veil}}$, L_{veil} was calculated by the Stiles-Holladay formula (Equation 3)

(2) $L_a = L_{\text{local}} + L_{\text{veil}}$, L_{veil} was calculated by the CIE General Disability Glare (Equation 4)

(3) $L_a = L_{\text{local}} + L_{\text{veil}}$, L_{veil} was calculated by Stiles-Crawford formula (Equation 5)

For the model calculation, L_{local} was assumed to be equal to the adaptation background luminance, which was 0.2 cd/m^2 . θ in the model 1 and 2 were interpreted as the visual angle between the target and the point source. For model 2, the average age of subjects (46 years) and eye pigment factor 0.5 (brown) was employed to calculate the CIE General Disability Glare equation.

The calculated effective adaptation luminances L_a as functions of the point source illuminance are shown in Figure 8. For the point source position of 7° and 15° , model 3 shows the best prediction, especially for 7° . The results of these conditions support that the surrounding luminance effect on the peripheral adaptation state can also be described as the veiling luminance. Evidence for non-linear factors, such as the lateral neural interaction, is not observed. Additionally, the magnitude is more consistent with the Stiles-Crawford formula, which is for the surrounding vision, rather than the foveal models.

However, all models overestimate the effective adaptation luminance for the point source position of 30° . This is probably due to the deviation between Equation 7 and real function for the detection threshold of the effective adaptation luminance. The real effective adaptation luminances for 30° should be slightly more than 0.2 cd/m^2 (adaptation background luminance), and less than 0.3 cd/m^2 . The uniform experiment results do not validate that the function in Equation 7 applies accurately in this low-level range. The real function may have a local minimum in this range. If this is true, the deviation between the models and experiment data for the point

source position of 30° can be explained. Whether or not, in terms of the uncertainty of the experiment method and analysis, the results of conditions with closer/brighter point source are more reliable to estimate the surrounding luminance effect on the adaptation state.

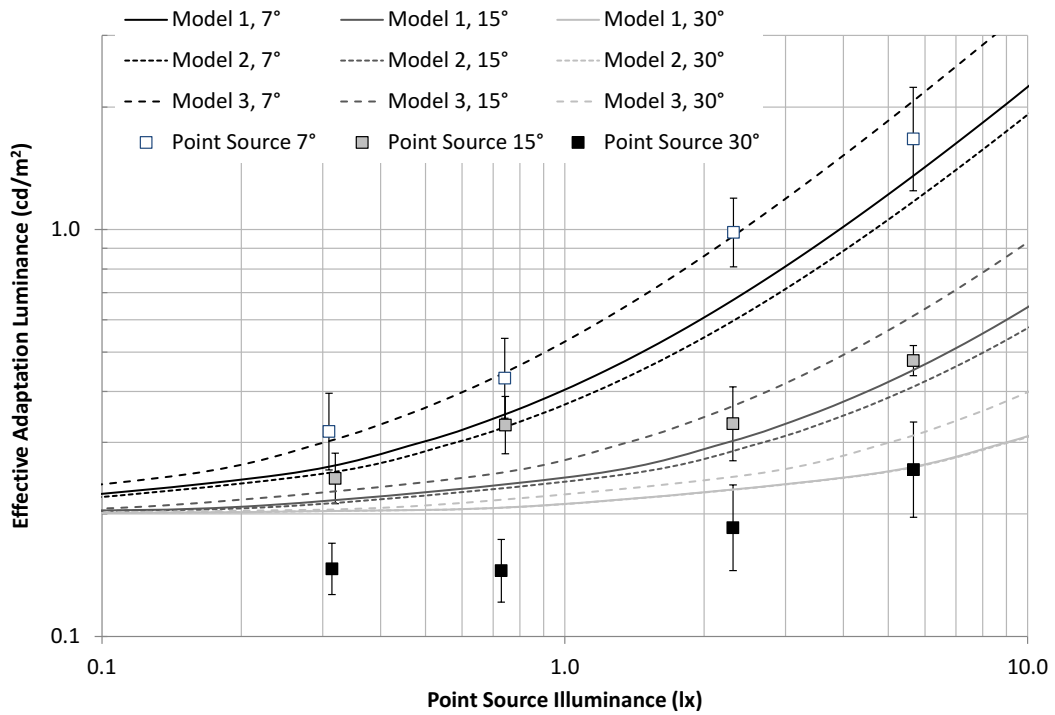


Figure 8 The effective adaptation luminances determined from the experiment results and the models, as functions of the vertical illuminance from the point source. Square symbols show the experiment results; white, gray, and black correspond to 7°, 15°, and 30°, respectively. Lines show the effective adaptation luminance from the models; Solid, short dashed, and long dashed lines correspond to the model 1, 2, and 3; Black, dark gray, and light gray correspond to 7°, 15°, and 30°, respectively

The surrounding luminance effect per 1 lx vertical/normal illuminance of the point source as a function of the visual angle between the point source and the task point is shown in Figure 9. Note that negative points for the point source position of 30° are omitted in Figure 9, because of the reason stated above. In Figure 9, the Stiles-Crawford formula shows the best prediction at 7° and 15° in three models. However, at 30°, the other two models are closer than the Stiles-Crawford formula. Overall, it seems that the Stiles-Crawford formula is the best predictor for the surrounding luminance effect on the peripheral adaptation state; however, further studies are needed for more confident conclusion for the angle characteristics.

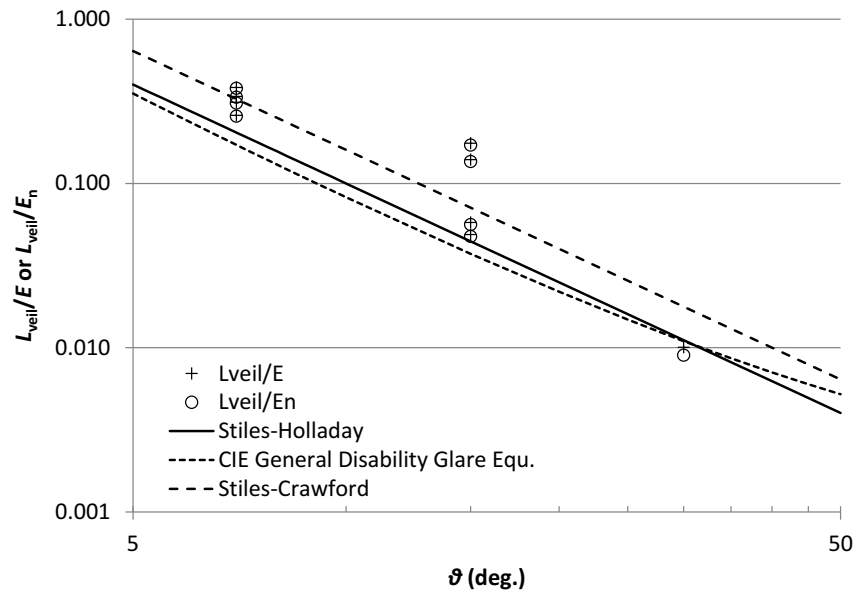


Figure 9 The surrounding luminance effects from the experiments (symbols) and the veiling luminance predicted with the models (lines), per 1lx vertical/normal illuminance from the point source. Plus symbols and circle symbols show the surrounding luminance effects divided by vertical

illuminances and normal illuminances, respectively

How significant is the surrounding luminance effect of the glare from road lighting luminaires, assuming that the surrounding luminance effect can be predicted with the Stiles-Crawford formula? To evaluate this impact, the mesopic luminance of a target was calculated for each lighting class in the CIE road lighting recommendation in CIE 115:2010.²³ The CIE recommendation, based on the road surface luminance, has requirements for upper limit of Threshold Increment (TI). TI is determined from the average luminance of the road surface and the veiling luminance (from direct light from the luminaires) calculated with the Stiles-Holladay formula.²⁴ Thus, when assuming a road lighting installation that has the average luminance of the road surface and TI listed in the recommendation, the surrounding luminance effect on the adaptation state and the mesopic luminance of the target can be calculated. In this calculation, the S/P ratio is assumed to be 2.4, which is the highest among those of commercially available sources listed in TM-12-12,²⁵ which is a technical memorandum published by Illuminating Engineering Society of North America (IESNA). It was also assumed that the difference between the vertical illuminance and the normal illuminance from glare sources can be neglected. This assumption allowed determining the surrounding luminance effect just by multiplying 1.6 to the veiling luminance based on the Stiles-Holladay formula.

Table 1 shows the calculation comparing two mesopic luminances of the target, the photopic luminance of which is 1 cd/m². One (on 8th column) is

calculated by using model 3 for the effective adaptation luminance calculation; another (on 11th column) is calculated by assuming that the effective adaptation luminance is equal to the average luminance of the road surface, neglecting the surrounding luminance effect. The right-end column shows the difference of two mesopic luminances in percent. Based on this analysis, the surrounding luminance effect decreases the mesopic luminance of the target by at most 4.67 %.

Note that these calculated differences on the mesopic luminance can be considered close to the largest estimations, when assuming observers' eye movement is fixed. Lower S/P ratio or lower TI makes the difference smaller. However, when taking into account observers' eye movement, and when the surrounding field of view is darker than the road surface as usual road lighting scene, the surrounding luminance effect may be more significant. This is because the local luminance L_{local} in the models can be considered the average luminance on where a peripheral task point on the retina focused, and the average luminance is lower than the average luminance of the road surface when the peripheral point scans the surrounding darker area. For this point, further studies with actual luminance distribution data are needed.

Another thing that should be noted is that the impact by the surrounding luminance calculated above is only for the changes in mesopic photometric quantities due to the changes in adaptation state. Since CIE mesopic photometry system is just designed to take the spectral sensitivity shift (Purkinje effect) into account, it does not predict all visual effects by

decreasing adaptation luminance, including the visual sensitivity improvement. According to Blackwell^{26,27} and CIE 19,²⁸ visual sensitivity (reciprocal of the luminance detection threshold) for 0.003 cd/m² is more than twelve times of that for 10 cd/m², while the ratio of the mesopic luminance of a test source that has an arbitrary photopic luminance for 0.003 cd/m² of adaptation luminance to that for 10 cd/m² of adaptation luminance is only about 1.4 when assuming that the light sources are incandescent lamps. Real task performance improvement on the peripheral vision should be more than the number (twelve times) based on Blackwell's research, because their experiments were conducted on fovea, where is mainly occupied by cones. There is also masking effect by veiling luminance from glare sources to peripheral task point, which was intentionally excluded from this study. These impacts on the peripheral task performance due to the changes in adaptation state, which are not taken into account by CIE mesopic photometry system, should be taken into account by road/street lighting recommendations based on peripheral tasks. This masking effect by glare sources can be measured by changing the experimental procedures, using the same set up we used.

Table 1 The impact of the surrounding luminance effect on the mesopic luminance of a target for the CIE road lighting classes

Lighting Class	CIE Recommendation		Veiling Luminance		$L_a = L_{av} + L_{veil}$ (Stiles-Crawford)			$L_a = L_{av}$			Diff.
	Average Luminance of the Road Surface	Threshold Increment	Stiles-Holladay	Stiles-Crawford**	Effective Adaptation Luminance		Mesopic Target Luminance*	Effective Adaptation Luminance		Mesopic Target Luminance*	
					$L_{p,a}$	$L_{mes,a}$		$L_{p,a}$	$L_{mes,a}$		
	L_{av} [cd/m ²]	TI [%]	L_{veil} [cd/m ²]	L_{veil} [cd/m ²]	$L_{p,a}$ [cd/m ²]	$L_{mes,a}$ [cd/m ²]	$L_{mes,t}$ [cd/m ²]	$L_{p,a}$ [cd/m ²]	$L_{mes,a}$ [cd/m ²]	$L_{mes,t}$ [cd/m ²]	
M1	2.00	10	0.27	0.43	2.43	2.57	1.06	2.00	2.15	1.07	1.57 %
M2	1.50	10	0.21	0.34	1.84	1.99	1.08	1.50	1.65	1.10	1.70 %
M3	1.00	15	0.23	0.37	1.37	1.52	1.11	1.00	1.14	1.14	2.70 %
M4	0.75	15	0.18	0.29	1.04	1.18	1.13	0.75	0.88	1.17	2.91 %
M5	0.50	15	0.13	0.21	0.71	0.83	1.17	0.50	0.61	1.21	3.24 %
M6	0.30	20	0.12	0.19	0.49	0.59	1.21	0.30	0.38	1.27	4.67 %

* Mesopic target luminance for photopic target luminance of 1 cd/m²

** Assuming that the vertical illuminance is equal to the normal illuminance

6 Conclusions

Experiments to measure the surrounding luminance effect by a high-luminance point source on adaptation state at a peripheral task point were conducted for possible definition of the adaptation field to implement the mesopic photometry system to lighting applications.

The results showed that the surrounding luminance effect can be described as the veiling luminance. However, the magnitude is larger than that on the fovea, and can be predicted with a model for the peripheral veiling luminance by Stiles and Crawford.²² Even though the angle characteristic also seems to be predicted with the same model, further study is needed for more confident conclusion. The surrounding luminance effect makes the direct light from luminaires decrease the mesopic luminance of a target; the negative difference on the mesopic luminance is less than 5 % for road lighting applications in compliance with the CIE road lighting recommendation.

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