Defining the visual adaptation field for mesopic photometry: Effect of a surrounding source position on peripheral adaptation

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Abstract

CIE 191:2010 from the International Commission on Illumination (CIE) recommends a mesopic photometry system based on peripheral visual tasks. For implementation of the system, the visual adaptation field needs to be defined, taking into account the surrounding luminance effect on the adaptation state. A series of vision experiments in the mesopic range has been conducted to measure the surrounding luminance effect with respect to the angle between a peripheral task point and a point source. The results show that the surrounding luminance effect at the peripheral task point decreases with the angle at a larger slope than existing models, such as Stiles-Holladay equation, CIE general disability glare formula, and Stiles-Crawford equation. Thus, a new model for the surrounding luminance effect has been proposed from the results.
1 Introduction

Determination of the adaptation luminance is a key issue for implementation of the mesopic photometry system recommended by International Commission on Illumination (CIE), which is expected to improve visual and/or energy efficiency of outdoor lighting applications [CIE 191]. Since the mesopic luminous efficiency function defined in the mesopic photometry system has its peak shifting to shorter wavelength depending on the adaptation luminance of observers, it has to be determined before measuring the mesopic quantities in a lit scene. Once the adaptation luminance and the luminous efficiency function are determined, the mesopic quantities in the scene, such as the mesopic luminance or the mesopic illuminance, can be measured with the luminous efficiency function [van Bommel 2015]. Pragmatically, defining a visual field that contributes the adaptation luminance is needed for the mesopic photometry system implementation. This visual field is usually called as ‘adaptation field’. Currently, CIE Joint Technical Committee 1 (JTC-1) is developing a technical report to address this issue [Pulakka and Halonen 2012].

Since the mesopic photometry system was developed based on peripheral task performance [Freiding et al. 2007, Walkey et al. 2007, Varady et al. 2007, He et al. 1997, He et al. 1998], the adaptation field should be defined
by taking the nature of peripheral adaptation mechanism into account. The adaptation state at a peripheral task point could be affected not only by the luminance at the point (local luminance), but also by the luminance of the adjacent area (surrounding luminance). Thus, the extent of the surrounding area, the luminance of which affects the adaptation state of the center point, is a fundamental and critical property to define the adaptation field.

The luminance of an area surrounding a task point could affect the adaptation state of the task point because of following two factors [TNO Report 2010, Cengiz et al. 2014]. The first factor is hereinafter called ‘surrounding luminance effect’, which makes the surrounding luminance influence the adaptation state even when the line of sight is fixed. Stray light inside the eyes (veiling luminance) or lateral neural interactions in the vision system are candidate mechanisms for the surrounding luminance effect. The second factor is the movement of line of sight, which depends on the lighting applications [Cengiz et al. 2014b, Heynderickx 2013, Winter and Völker 2013]. This factor broadens the area that affects the adaptation state determined by the first factor.

Authors have been studying the first factor, surrounding luminance effect [Uchida and Ohno 2014a, Uchida and Ohno 2014b]. Those experimental studies show that: the adaptation luminance at a peripheral task point
predominantly depends on the local luminance but is also slightly affected by the surrounding luminance [Uchida and Ohno 2014a]; and the surrounding luminance effect by a point source can be predicted with a model like the veiling luminance models [Uchida and Ohno 2014b]. In those studies, the adaptation luminance including both the local luminance and the surrounding luminance effect has been named ‘effective adaptation luminance’ to distinguish it from the local luminance clearly. The model for the effective adaptation luminance $L_{a,\text{effective}}$ is

$$L_{a,\text{effective}} = L_{\text{local}} + L_{\text{veil}}$$

(1)

where $L_{\text{local}}$ is the local luminance at the task point and $L_{\text{veil}}$ is the surrounding luminance effect, which is caused by the surrounding luminance. The surrounding luminance effect is basically not significant for the luminance level of lit objects, but may be significant for light sources such as luminaires. Thus, the surrounding luminance effect by a point source was measured in the previous study [Uchida and Ohno 2014b]. For the results, a peripheral veiling luminance model by Stiles and Crawford [Stiles and Crawford 1937] showed better prediction for $L_{\text{veil}}$ than other models. It is

$$L_{\text{veil}} = \frac{16}{\theta^2} E_n$$

(2)

where $E_n$ is the normal illuminance (illuminance on a plane perpendicular
to the direction from the source) at the eye due to a point source in the surrounding area, and \( \theta \) is visual angle between the point source and a task point where the veiling luminance is caused. The model can accurately predict the experiment results for \( \theta = 7^\circ \) in the illuminance range of 0.3 lx \( \leq E_n \leq 5.4 \) lx. However, it is not clear whether the model can predict the surrounding luminance effect for other angle \( \theta \) with the same level of accuracy. In the previous study, only three angle conditions, 5\(^\circ\), 15\(^\circ\), and 30\(^\circ\), were employed in the experiment and Stiles-Crawford model still shows some deviations from the experimental results for 15\(^\circ\) and 30\(^\circ\).

Therefore, the purpose of this study is to test if veiling models, including Stiles-Crawford model, can predict the surrounding luminance effect on the adaptation state at a peripheral task point in wide range of visual angle \( \theta \). For this purpose, a series of visual experiments was conducted with various angle conditions.

2 Method

The principle of the experiment in this study was the same as the previous study by authors [Uchida and Ohno 2014b]. The subjects performed luminance contrast detection tasks after fully adapted to patterns with a point source at various positions. All conditions except for
the adaptation pattern, such as the background luminance when the target was presented, the target duration and the target size for the detection task, were constant for all experimental conditions. A point source was presented just during the adaptation phase and was turned off during detection task phase. If the point source stays on for both phases, it can affect the task performance in two ways: by changing the adaptation state and by reducing the luminance contrast between the target and its background. To remove the luminance contrast reduction, the point source was turned off just during the target presentation. Since the time constant of the adaptation mechanism is long enough, the adaptation state was maintained at almost the same level during the absent of the point source [Narisada 1992]. This procedure allows us to estimate the adaptation state from the threshold contrast.

### 2.1 Set-up

A schematic diagram of the experimental set-up is shown in Figure 1. All experiments were conducted in a darkroom.
**Figure 1** Depiction of the experimental set-up

**Figure 2** Schematic elevation of the LEDs, the jig, and the LCD
A liquid crystal display (LCD) controlled by a computer was employed to present the target to be detected and the background. The LCD was covered with neutral density (ND) films to reduce the luminance level to a mesopic range, but maintain high-resolution (1024 levels) control of the luminance level by the computer. The target and the background presented by the LCD were white. The correlated colour temperature (CCT) and scotopic/photopic (S/P) ratio of these were 4690 K and 2.21, respectively.

Eight white light emitting diode (LED) units were used as point sources, and were placed in front of the LCD at 4 cm from the LCD surface. Only one of the LEDs was turned on for an experimental condition. Each LED unit was a chip-on-board (CoB) LED package with a diameter of emission surface of 15 mm. Those were fixed on an aluminum jig with heat conductive paste so that the heat from LEDs was released effectively. A schematic depicting the elevation of the CoB LEDs, the jig, and the LCD is shown in Figure 2. The LEDs were driven with a multi-channel DC current source controlled by the computer. The luminous intensity of LEDs was dimmed by changing the current level from 2 mA to 95 mA. For the current of 40 mA, the average CCT and average S/P ratio of the LEDs were 6090 K and 1.99. The chromaticity change caused by the current change was less than 0.003 in \( u', v' \) coordinate, which can be considered insignificant for the experiment.
It was also checked that the temporal change of the luminous intensity and the chromaticity of LEDs during an experimental session were negligible. Care was taken so that no light from the LEDs fell on the LCD screen.

The subject was positioned at a viewing distance of 65 cm from the screen and fixed his/her head on a chin rest during each experimental run. At this distance, the LCD screen subtended $49^\circ \times 29^\circ$ visual angle from the subject’s eyes. The subject responded by clicking a mouse button to answer whether he/she saw the target or not. Then, the computer logged the response automatically.

Prior to every experimental session, the LCD was warmed up to ensure that stabilization had been reached. Then the luminance at the target position on the LCD screen was calibrated by using a luminance meter placed at the subject’s eye position. The vertical illuminance from the point source at the subject’s eye position was also calibrated by an illuminance meter before every experimental session. To reduce the spectral mismatch error, the luminance meter and the illuminance meter were calibrated with a spectroradiometer (calibrated against NIST spectral irradiance scale) measuring the particular LCD and LED used in the experiment, respectively.

The expanded uncertainties ($k=2$) of the measured luminance,
illuminance, CCT, and S/P ratio in this paper were 2.0%, 2.0%, 70 K, and 0.02, respectively.

### 2.2 Stimuli

Adaptation patterns and a task pattern employed in the experiment are shown in Figure 3. The adaptation patterns, shown in the top row in Figure 3, were luminance distributions consisting of the LCD and the LED, to which the subject adapted. The task pattern, shown in the bottom row in Figure 3, was only a luminance distribution displayed on the LCD, on which the subject performed the detection tasks. These two types of patterns were switched sequentially to remove the point source just at the moment of the detection task. The sequence will be described later.
**Figure 3** Adaptation patterns and task patterns used for the experiment.

The top row shows the adaptation patterns, and the bottom row shows the task patterns, for each condition.

For every pattern, the bottom half part of the LCD screen was uniformly set at a luminance level. Hereinafter, this luminance will be referred as ‘adaptation background luminance’ for an adaptation pattern and ‘task background luminance’ for a task pattern. The luminance of the top half part of the LCD was set as low as possible, which was less than 0.001 cd/m². The subject was asked to fix their line of sight to a fixation point, which was shown as a small cross on the screen. The fixation point moved around a central area of the screen as described later, but it was always at the centre of the screen while the task pattern was presented. The target to be detected always appeared at lower right of the fixation point. The eccentricity of the target (the visual angle between the target and the fixation point) was 10°. This position will be referred as ‘task point’ regardless of the type of pattern. The diameter of the target was 1° of visual angle.

According to the existence or the position of the point source in the adaptation pattern, the experimental conditions were sorted into three groups: near-point-source conditions (four conditions), far-point-source conditions (four conditions), and reference conditions (two conditions). The
near- and far-point-source conditions had a point source right above the task point in the adaptation pattern, but the visual angle from the task point to the point source, $\theta$, and the vertical illuminance at the subject's eye position from the point source, $E_v$, were different for each condition. The visual angles $\theta$ were: $5^\circ$, $7^\circ$, $10^\circ$, and $15^\circ$ for the near-point-source conditions; $20^\circ$, $25^\circ$, $30^\circ$, and $40^\circ$ for the far-point-source conditions. The vertical illuminances $E_v$ for the near- and far-point-source conditions were 3 lx and 45 lx, respectively. The adaptation background luminance was 0.2 cd/m$^2$ for all point-source conditions. For the reference conditions, the adaptation pattern did not have any point sources. The adaptation background luminance was 0.2 cd/m$^2$ and 2.0 cd/m$^2$. The task pattern was the same for all conditions. The task background luminance was always 0.2 cd/m$^2$.

2.3 Procedure

An experimental session consisted of six conditions: four point-source conditions (near- or far-) and the two reference conditions. Each subject was asked to complete two experimental sessions. Thus, each subject performed each point-source condition once, and each reference condition twice. The sequence of the condition was basically random, but the reference conditions were always conducted third or fourth so that the effect of the subject’s
fatigue can be removed from the comparison of the reference condition results between experimental sessions.

In the beginning of 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. Then the first condition was started. The adaptation pattern was presented for five minutes at first. For photobiological safety consideration, i.e. to avoid the point source excessively stimulate a fixed point on the subject’s retina, the fixation point was moved around a $2^\circ \times 5^\circ$ oval area centred at the centre of the screen during this adaptation pattern presentation.

After the adaptation, the subject started a trial by clicking a mouse button. The pattern was switched to the task pattern for 0.6 s. The target was presented at the middle 0.2 s of the task pattern presentation. During the task pattern presentation, the fixation point was fixed at the centre of the screen. The colour of the fixation cross was changed from black to white when the target was presented. This is to give the subject the same cue of the target presentation timing for both the point-source conditions and the reference conditions.

The subject answered whether he/she saw the target or not, by clicking one of the mouse buttons. After the response, the adaptation pattern was
presented for 5 s to keep the adaptation state of the subject’s eyes. The fixation cross moved around the centre of the screen in the same manner as the first adaptation phase. Then the next trial started.

The trials were repeated until enough data to determine a luminance contrast detection threshold were collected, according to the random-staircase method.

2.4 Subjects

Nine subjects with normal vision participated in the experiments. Their ages were 27 to 70 years. Two of them were younger than 30 years, three of them were younger than 40 years, another three of them were younger than 50 years, and the other one was 70 years. Four of them had dark-brown eyes, other four had brown eyes.

3 Results

The mean luminance contrast detection thresholds of all subjects are shown in Figure 4 and 5 for the near-point-source conditions and the far-point-source conditions, respectively. All conditions in each figure were conducted in one experimental session. The luminance contrast detection threshold \( C_{th} \) was calculated as
\[ C_{th} = \frac{L_b - L_t}{L_b} \]  

where \( L_b \) is the task background luminance and \( L_t \) is the target luminance at the threshold. For a comparison purpose, results of the reference conditions in the same experimental session were plotted in the same figures, at the left end of each graph, which is noted as “Ref.” on the abscissa.

The experimental results are basically consistent with our previous study [Uchida and Ohno 2014b]. A basic observation from the experiment results is that higher effective adaptation luminance causes higher detection threshold contrast. This can be suggested from the reference conditions’ results. For the reference conditions, higher adaptation background luminance, the effective adaptation luminance of which is obviously higher than the other reference condition, causes higher threshold contrast.

Based on this empirically verified hypothesis, the point-source conditions’ results suggest that a nearer point source increases the effective adaptation luminance more. It is reasonable that the difference of the detection threshold, which means the difference of the effective adaptation luminance, was caused by the change of the surrounding luminance effect by the position and the illuminance of the point source. Note that the illuminance from the near point sources is only 3 lx while that from the far point source
is 45 lx, which is 15 times higher. If the illuminance of the far point sources had been the same as that of the near point sources, the thresholds would have been much lower than those shown in Figure 5 and the effect would have been too small to measure by the experiment.

By contrast, the detection threshold for 5° is much higher than others, even though the point source has only 3 lx of vertical illuminance at the subject’s eye position. Although our previous study has shown that the relation between the detection threshold and the logarithm of the effective adaptation luminance is linear, the result for 5° is out of the range in which the linear relation has been shown.

The detection thresholds for the reference conditions with 2.0 cd/m² of the adaptation luminance are 10.5 % and 11.1 % in Figure 4 and Figure 5, respectively. Those with 0.2 cd/m² are 7.1 % and 6.8 %. The differences between the experimental sessions, which are smaller than the differences between the results of the conditions in an experimental session, mean that the experiment has good enough repeatability to compare the results between the sessions.
Figure 4 The mean luminance contrast detection thresholds for all subjects for the near-point-source conditions and the reference conditions performed in the same session.

Figure 5 The mean luminance contrast detection thresholds for all subjects for the far-point-source conditions and the reference conditions performed in
the same session

4 Discussion

The effective adaptation luminances for the point source conditions, including both the adaptation background luminance and the surrounding luminance effect, were determined from the detection thresholds by introducing an assumption verified in our previous empirical study [Uchida and Ohno 2014b]. The assumption is expressed as an equation

\[ C_{th} = a \log_{10} L_{a,\text{effective}} + b \]  

(4)

where \( a \) and \( b \) are coefficients. Those were determined by substituting the adaptation background luminances and the detection threshold contrasts of the two reference conditions for \( L_{a,\text{effective}} \) and \( C_{th} \), respectively. Once the coefficients were determined, the effective adaptation luminance for each point source condition can be calculated from the detection threshold contrast for each condition with Equation 4. Then, the surrounding luminance effect \( L_{\text{veil}} \) for each condition was determined by using Equation 1. For this calculation, the adaptation background luminance, which was always 0.2 cd/m\(^2\) for all point-source conditions, was used as the local luminance \( L_{\text{local}} \) in Equation 1. Finally, the surrounding luminance effect was divided by the vertical illuminance \( E_v \) or the normal illuminance \( E_n \) at the eye position for each condition to cancel the difference of the
illuminances between the near-point-source condition and the far-point-source condition.

The determined surrounding luminance effects per 1 lx of the vertical illuminance and the normal illuminance for each condition were shown in Figure 6. As shown in Figure 6, the difference caused by which illuminance was used to derive the value is not significant to evaluate the angular characteristics of the surrounding luminance effect. The same quantities derived from the previous experiments also plotted in the same figure with different symbols.

Existing three veiling luminance models are plotted as thin lines in the figure. Those are Stiles-Crawford equation [Stiles and Crawford 1937] (Equation 2), Stiles-Holladay equation [CIE 1942], and CIE general disability glare formula [CIE 146]. As shown in Figure 6, none of them seems to predict the experimental results well through the whole range of the visual angle. The trend of the experimental results seems steeper than those of the existing models.

Thus, a new model was developed to provide more accurate prediction for the experimental results. Unfortunately, we considered that the result for 5° should not be taken into account for the new model. Although the process to determine the effective adaptation luminance relies on the linear relation
between the detection threshold and the logarithm of the adaptation luminance, it was verified only in a range between and around the two levels of the adaptation background luminances for the reference conditions. As stated in Section 3, the detection threshold for 5° point-source condition is out and away from the range. On the other hand, the experimental results of the previous study were taken into account for the new mode. The new model, which was given based on a regression line for the surrounding luminance effect per 1 lx for all experimental results, is

\[ L_{\text{veil}} = \frac{260}{\theta^2} E_V. \]  

(2)

It is plotted as a thick line in Figure 6. The graph shows that the new model can predict the experimental results better than the existing models.

The experimental results do not give any suggestion why the new model is different from the existing models. However, hypotheses can be deducted from existing knowledge. It may be due to the difference of the receptive field size between fovea and the peripheral field, or difference of stray light inside the eyes. For example, larger receptive field of retinal ganglion cells in peripheral field than that in the fovea [Hubel D] can be considered as a reason of the larger surrounding luminance effect.

There are some limitations for the model. Firstly, the model represents only the task performance at the particular task point. Also, the angular
characteristic was measured in the particular direction, which was right above the task point. When the locations of task point or the direction of the source is different, the angular characteristic may also be different from the model. A lower limit of the visual angle that the model can be applied is also unclear. Further research is needed to overcome those limitations.

However, when the luminaires on a street or a road are main sources of the surrounding luminance effect, it is reasonable to apply the model. This is because the adaptation patterns for the point-source conditions are analogous to the street or road lighting scenes: the bright bottom part of the screen corresponds a lit road surface and the point source corresponds a luminaire.
Figure 6 The surrounding luminance effects from the experiments (symbols) and the veiling luminance predicted with the models (lines), per 1 lx of vertical or normal illuminance from the point source.

5 Conclusions

Experiments to measure the surrounding luminance effect by a point source on adaptation state at a peripheral task point were conducted to clarify the angular characteristic of the effect, which is considered as a key factor to define the adaptation field for implementation of the mesopic photometry system to lighting applications.

The results were consistent with our previous study, which showed the surrounding luminance effect can be described as the veiling luminance. By comparing the experimental results with existing models, it is suggested that the surrounding luminance effect decreases more rapidly with the visual angle between the task point and the point source than the existing models’ predictions. Therefore, a new model, which can more accurately predict the experimental results, has been proposed. It could be suitable to predict the surrounding luminance effect from luminaires in street or road lighting scenes.

For a definition of the adaptation field for the mesopic photometry system, the effective adaptation luminance including the surrounding
luminance effect should be evaluated for real lit scenes with the model. This is an interesting subject for further research.

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**References**


4. [Freiding et al. 2007] Freiding A, Eloholma M, Ketomäki J, Halonen L,


2010.


15 [Uchida and Ohno 2014b] Uchida T and Ohno Y. Defining the visual
adaptation field for mesopic photometry: How does a high-luminance source affect peripheral adaptation? Lighting Research and Technology 2014; DOI: 10.1177/1477153514558963 (online).


