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COMPARATIVE STUDY OF TWO VISUAL PERFORMANCE BASED MESOPIC MODELS BASED ON REACTION TIME AND CONTRAST THRESHOLD DATA

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In this work reaction time and contrast threshold were measured to evaluate mesopic visual performance at two light levels (0.1 and 1 cd/m^2) in different spectral conditions and at different target contrasts in peripheral vision. The magnitude of the effect of SPD (spectral power distribution) on visual performance in different mesopic conditions was investigated and the relationship between reaction time and contrast threshold was studied. The new data sets were applied to two recently introduced performance based mesopic models, the MOVE-model and the X-model, and the models' predictions of mesopic luminances were evaluated. The two models were not consistent in predicting mesopic performance. The reasons for the divergences in the models may be the different parameter conditions under which the models were established. Before proposing a model for mesopic photometry there should be more data for comparing the existing models and this data should be based on parameters relevant in night-time driving conditions. The CIE TC1-58 is working on to acknowledge the essential parameters to be used in further testing and validating the visual performance based mesopic models.

Key words: visual performance, mesopic model, photometry, reaction time, contrast threshold, road lighting

1. Introduction

Photometry provides a method with which light can be assessed in terms of human visual spectral sensitivity. Spectral sensitivity functions are derived from psychophysical experiments based on the use of certain visual criteria and a defined set of lighting and viewing conditions. Both the psychophysical criteria and the physical conditions of the experiments affect the derived functions [1].

There is currently no officially recommended CIE (Commission Internationale de l'Eclairage) system for measuring light at mesopic levels. Photopic photometers are frequently used at these levels resulting in measurements that do not match with visual perception. This is especially true with light sources having considerable amount of their radiation in the blue region, for example modern discharge lamps and LEDs (light-emitting diodes).

Mesopic lighting applications are of substantial practical interest as they include road lighting, outdoor lighting, other night-time traffic environments, emergency lighting, and many other applications. It is especially the higher part of the mesopic luminance region that is most important for practical applications (e.g., traffic lighting) and for which new measurement methods and a practical system of mesopic photometry are very much needed [1].

The development of mesopic photometry has raised interest in the international lighting community for several decades. In 1989, the CIE reported on five mesopic photometric models based on brightness matching [2]. These models describe the shift of spectral sensitivity towards shorter wavelengths with decreasing luminance levels in the mesopic region. In 2001 the CIE updated the earlier report and published a new report where six models based on heterochromatic brightness matching for 10° fields were presented [3]. In this report each model was subjected to quantitative tests of its agreement with the data from several brightness matching experiments. The testing did not provide the selection of one best model and the report made no recommendation for a new CIE supplementary system of photometry. The mesopic models based on brightness adequately predict the brightness of monochromatic lights. However, the additivity failures became apparent when predictions of the brightness of non-monochromatic lights are made [1].

Visual performance based mesopic photometry has been a topic of study in recent years. The CIE has established a special technical committee TC 1-58 to investigate performance based photometry in the luminance region below approximately 10 cd/m^2 and to propose a model for the basis of performance based mesopic photometry [4]. Visual performance is conventionally defined by the lighting research community as the speed and accuracy of performing a visual task. The speed and accuracy are useful measures of performance and are directly related to driving performance where early recognition of obstacles and dangerous situations are important. Reaction time task has been divided into the visual component (seeing the target), cognitive component (noting that something is present) and the motor component (manually responding to the onset of the target) [6]. Reaction time has been argued to be a relevant measure to quantify visual performance because of having proportionally small non-visual contributions to the observed response [6]. In developing visual performance based mesopic models reaction times have been one measure of performance [7, 8]. Also other visual tasks, such as contrast threshold, detection rate, search time and visual acuity have been used [9, 10, 11, 12].

Two visual performance based mesopic models have been recently published, the X-model [13] and the MOVE- model [12]. Rea et al. [13] proposed the X-model as a unified system of photometry based on the two earlier experiments of reaction time by He et al [7, 8]. The underlying visual experiments of the X-model are based on reaction time data of three observers. The X-model describes mesopic luminous efficiency $V_{mes}(\lambda)$ as a linear transition between the scotopic $V'(\lambda)$ and the photopic $V(\lambda)$ functions in the mesopic region as

$$V_{mes}(\lambda) = XV(\lambda) + (1-X)V'(\lambda) \qquad (1)$$

$$X = \frac{1}{0.599} L_m - \frac{0.001}{0.599}$$

where the X is a parameter characterizing the proportion of the photopic luminous efficiency at any luminance level. Below 0.001 cd/m^2, $X = 0$ and above 0.6 cd/m^2, $X = 1$.

The MOVE model [12] was developed based on experimental work carried out in several test locations using different visual criteria and experimental settings. In addition to reaction time, contrast threshold and recognition threshold were used as the visual tasks in the experiments. All experiments were based on a common set of parameter values and altogether 109 observers participated in the experiments. The MOVE model is of the form

$$M(x)V_{MOVE}(\lambda) = xV(\lambda) + (1-x)V'(\lambda) \qquad (2)$$

$$x = 1.49 + 0.282 \log_{10} I_m(x, L_p, L_s)$$

$$I_m(x) = \frac{L_m(x)}{K(x)} = \frac{V_{MOVE}(\lambda_0, x)}{683} L_m(x)$$

where $V_{MOVE}(\lambda)$ represents the relative spectral luminous efficiency function and $M(x)$ is a normalizing function such that $V_{MOVE}(\lambda)$ attains a maximum value of 1. The proportions of the photopic and scotopic functions are determined by parameter x. The parameter itself is determined by an iterative approach for a given background light level and background light spectrum. The photopic luminance L_p (weighted with $V(\lambda)$) and the scotopic luminance L_s (weighted with $V'(\lambda)$) of the background are needed for determining the value of x by iteration. $I_m(x)$ is defined as the ratio of $L_m(x)$ to $K(x)$. $L_m(x)$ is mesopic luminance and $K(x)$ is the maximum spectral luminous efficacy which makes the curves $K(x)V_{mes}(\lambda, x)$ all take the value 683 at $\lambda_0 = 555$ nm.

In the present work reaction time (RT) and contrast threshold (CT) were selected as the criteria of visual performance and these were measured at two

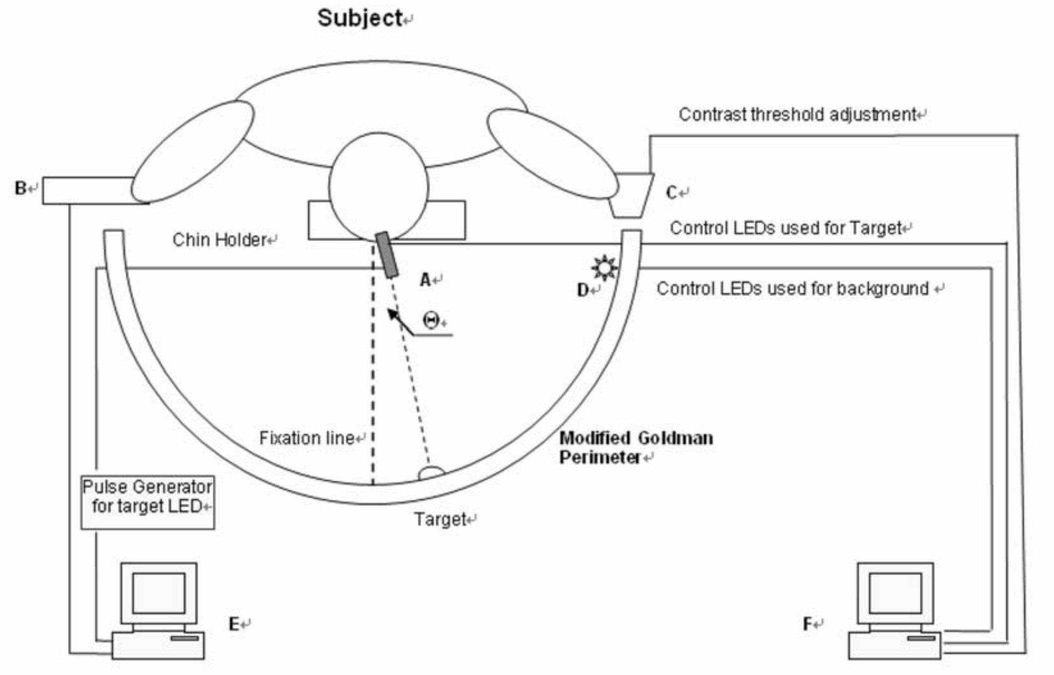


Fig. 1. Schematic layout of the experimental set-up

A – LED to generate a light spot on the perimeter surface as a visual target. B – Reaction time response button controlled by the subject. C – Contrast threshold control knob to adjust the target contrast. D – LED to illuminate the surface of the perimeter. A number of LEDs were installed at the hemisphere outer segment. E – Computer to control the Pulse Generator to display visual target and record the reaction time. F – Computer to control the luminance of the background and visual target and record the contrast threshold. Θ – angle of eccentricity 10° horizontally

light levels (0.1 and 1 cd/m^2) using 10° target eccentricity. Four coloured lights (blue, green, amber, red LEDs) with different SPDs were used to illuminate the background and the visual target. The half-bandwidths of the LEDs were hbw = 16-37 nm. The target was superimposed on the background, thus in each spectral condition the target and background spectra were the same.

The first objective of this work was to study the relationship between visual performance (in terms of reaction time and contrast threshold) and different visual parameters (luminance, contrast and SPD) at mesopic levels. The aim was to study the magnitude of the effect of SPD on visual performance at different luminance levels and target contrasts. A further objective was to compare the reaction time and contrast threshold behaviour in relation to lighting conditions in the mesopic region.

The objective was also to compare the results of RT and CT with the predicted values of mesopic luminances calculated using both the X-model and the MOVE-model. The two models were used to calculate mesopic luminances from the photopic luminances and S/P-ratios of the different experimental parameters. The two visual performance based mesopic models were compared in terms of their prediction of reaction time and contrast threshold behaviour as a function of light level.

2. Method

2.1. Subjects

Five subjects, one female and four male aged 24-33 years (mean 29) participated in the experiments. The subjects have normal visual acuity and color vision. No ocular pathology was reported. All the subjects understood the purpose and the procedure of the experiments very well.

2.2. Experimental set-up

Reaction time and contrast threshold were measured using a modified Goldman perimeter which is a white painted hemisphere with a diameter of 600 mm. A 2° light spot was projected on the surface of the hemisphere as a visual target. Figure 1 shows the schematic layout of the experimental setting in a dark room from top view. A number of LEDs were positioned around the edge of the hemisphere to distribute the light to the background uniformly. One LED located on the upper edge of the hemisphere to

Table 1

Values of parameters used in the experiments

Parameters		Values
Fixed parameters	Adaptation time	10 min before the first experimental trial and 5 min between different background light levels
	Stimulus duration in RT experiment	1000 ms
	Viewing	Monocular (left eye)
	Eccentricity Θ	10°
	Target size	2°
Variable parameters	Background luminance L_p (photopically weighted)	0.1 and 1 cd/m^2
	Target contrast C	$C = 0.1$ and 0.15 for $L_p = 0.1$ cd/m^2 $C = 0.05$ and 0.1 for $L_p = 1$ cd/m^2
	Spectral power distribution	blue, green, amber, and red

generate the light spot extending a visual angle of 2° to subject's eye at the eccentricity of 10° horizontally. The hemisphere surface luminance and the visual target luminance could be independently controlled by computer. A computer controlled the Pulse Generator to display the visual target and record the reaction time. A response button was used by the subject in the RT measurements and a control knob to increase the target contrast in the CT measurements. In the CT experiments the subject was asked to increase the luminance of the target until the target became just visible.

2.3. Measurement procedure

The experimental conditions are summarized in Table 1. There were two photopic ($V(\lambda)$-weighted) background luminances (L_p = 0.1 and 1 cd/m^2), two contrasts ($C = 0.1$ and 0.15 for $L_p = 0.1$ cd/m^2, $C = 0.05$ and 0.1 for $L_p = 1$ cd/m^2) and four light spectra (blue, green, amber and red) used in the experiments. Each subject finished these 16 different experimental conditions in two hours. In each condition, 24 measured values of reaction time and 5 measured values of contrast threshold were recorded. The presentation order of the 16 different experimental conditions was randomized for each subject. The spectral distribution of the LEDs used to illuminate the background and the target are shown in Figure 2.

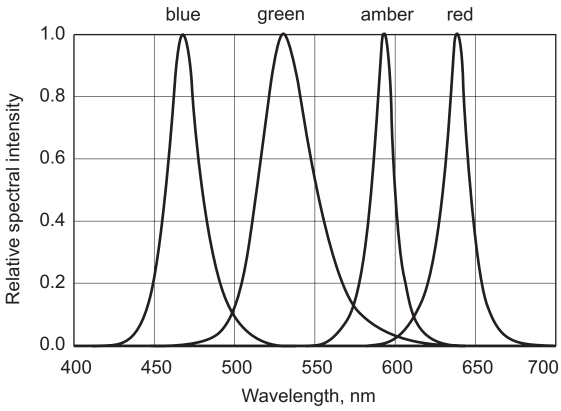


Fig. 2. The relative spectral power distributions of the blue, green, amber, and red LEDs used in the experiments

For each experimental condition, the test was divided into two stages. In the first stage the subject controlled the button (B) by right hand to perform the reaction time experiment. In the second stage the subject was asked to adjust the control knob (C) by left hand to increase the luminance of the target to perform the contrast threshold experiment. The subject was adapted to the background luminance for 5 minutes before each test with different background luminance began. During the experiments, the subject was asked to fixate his/her left eye on the small cross in the center of the perimeter.

In the RT experiments the target was projected at the 10° eccentricity after a random time delay from 2 to 4 seconds, and the subject pressed the response button as soon as the target was detected. The target was a square-wave shaped flash-like stimuli of 1000 ms duration. A maximum of 1 second following

Table 2

The mean value of contrast threshold (CT) and reaction time (RT) for the five subjects in each experimental condition

Spectrum	S/P- ratio	RT				CT	
		L_p = = 1 cd/m^2, C = 0.1	L_p = = 1 cd/m^2, C = 0.05	L_p = = 0.1 cd/m^2, C = 0.15	L_p = = 0.1 cd/m^2, C = 0.1	L_p = = 1 cd/m^2	L_p = = 0.1 cd/m^2
Blue	13.9	284.6	342.1	299.6	329.0	0.036	0.053
Green	2.09	294.6	347.2	334.9	367.2	0.039	0.065
Amber	0.239	293.1	337.3	380.3	426.2	0.040	0.086
Red	0.0396	303.0	392.2	409.3	511.9	0.043	0.114

Table 3

The result of Analysis of Variance for reaction time (RT) and contrast threshold (CT) data

Experimental method	Experimental conditions	Source Term	DF	Sum of Squares	Mean Square	F-Ratio	p-value
RT	L = 1 cd/m^2; C = 0.1	Spectrum	3	20286	6762	2.55	0.055433
	L = 1 cd/m^2; C = 0.05	Spectrum	3	212155	70719	16.05	0.000000*
	L = 0.1 cd/m2; C = 0.15	Spectrum	3	822454	274151	77.46	0.000000*
	L = 0.1 cd/m2; C = 0.1	Spectrum	3	2045175	681725	124.32	0.000000*
CT	L = 0.1 cd/m^2	Spectrum	3	0.1092615	0.0364205	111.86	0.000000*
	L = 1 cd/m^2	Spectrum	3	0.001116	0.000372	5.76	0.000850*

* Term significant at alpha = 0.05

the onset of the target was allowed for response. The time between target display and response was recorded as the reaction time.

Contrast threshold was measured by luminance increment of the target at the detection threshold. The luminance of target was monitored by the computer software (F) in 250 steps. The luminance corresponding to each digital value for the different light spectra was measured and calibrated before the experiments. When the subject controlled the button (B) to increase target luminance the corresponding digital values in the software were recorded and were later on calculated to luminance values by using pre-calibrated calculation system. The contrast values in this work are defined as

$$C = \frac{L_t - L_b}{L_b} \qquad (3)$$

where L_t is the luminance ($V(\lambda)$-weighted) of target and L_b is the luminance ($V(\lambda)$-weighted) of background.

3. Results

Totally 1920 measured values of reaction time and 400 measured values of contrast threshold were recorded in the experiments. The measurement results were analyzed by the statistical software NCSS 2001 with the method of MANOVA ($p \leq 0.05$). The mean values of RT and CT of all the trials and five subjects are showed in Table 2. The RT data smaller than 100 ms or higher than 800 ms are recorded as missed pulses and these are not included in the calculation of the mean values. Of the total value of measured reaction times 2.8% were missed pulses and over 50% of these were recorded for the red light.

The results of analysis of variance for the RT and CT data are shown in Table 3, where DF denotes to degree of freedom and F-Ratio to the ratio of the Mean Square to the Error Mean Square. When L = 1 cd/m^2 and C = 0.1, the p-value is > 0.05 and show no statistically significant difference in RT between light spectra. In all the other three experi-

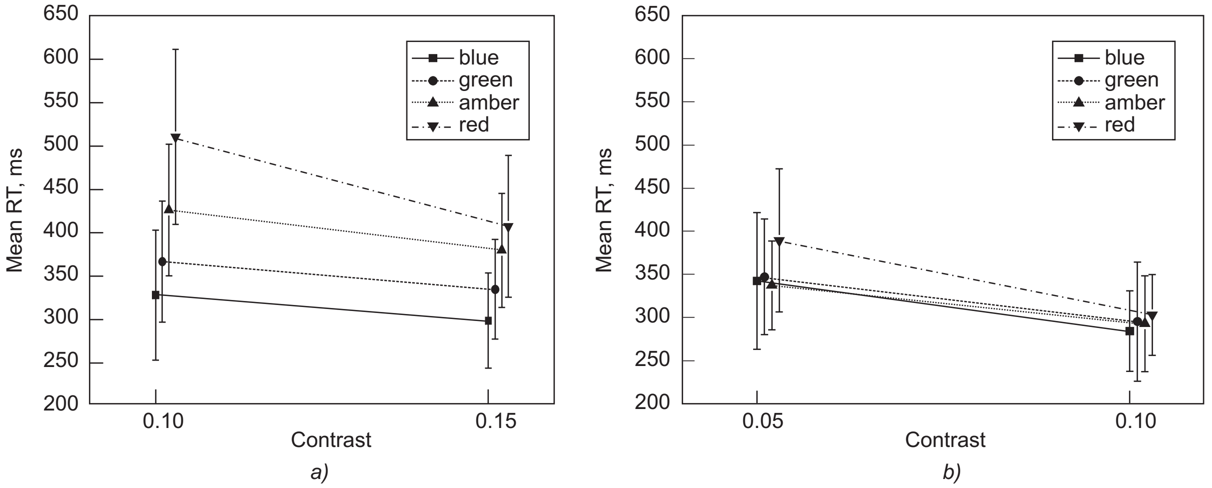


Fig. 3. Mean and standard deviation of reaction time (RT) plotted against target contrast, for four spectra (blue, green, amber, and red) and at background luminance levels

a) $L_p = 0.1$ cd/m^2 and *b)* $L_p = 1$ cd/m^2

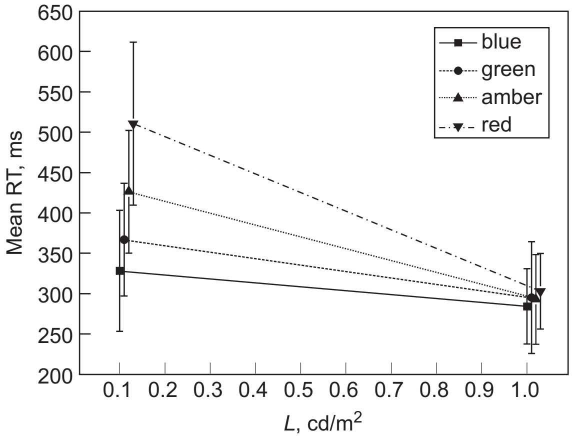


Fig. 4. Mean and standard deviation of reaction time (RT) plotted against background luminance at $C = 0.10$, for four light spectra (blue, green, amber and red)

mental conditions a statistically significant difference in RT between different spectra was found. For CT the effects of light spectrum were found at both luminance levels, however the spectral effects were more pronounced at the lower luminance level $L = 0.1$ cd/m^2.

3.1. Reaction time

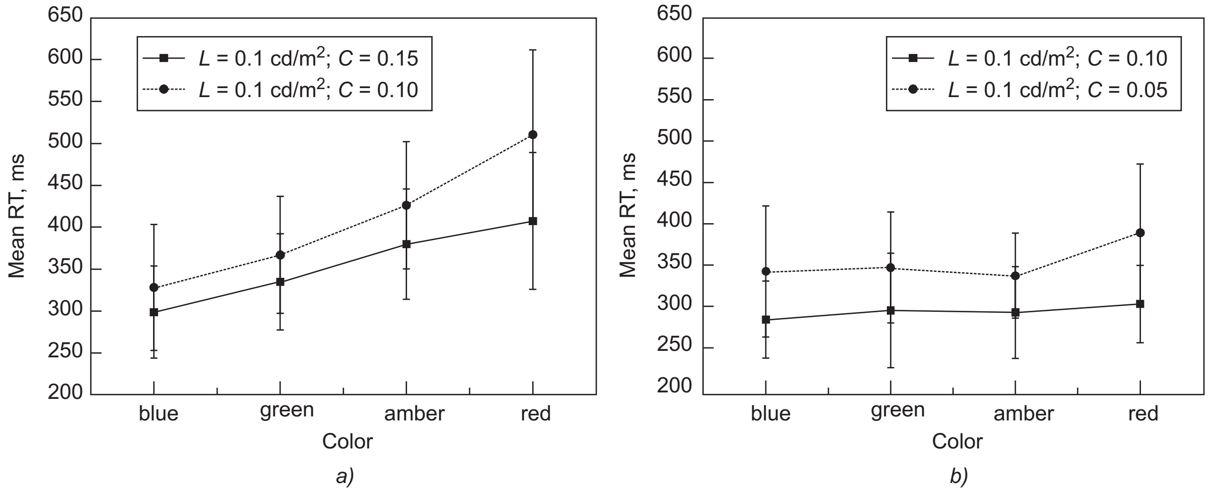
3.1.1. The effects of contrast and luminance on reaction time

Figure 3 shows the results of the RT measurements at the two target contrasts for the four different light spectra at both background luminance levels. There was a clear and statistically significant decrease in reaction time with increasing contrast. This was found at both background luminance levels ($L_p = 0.1$ cd/m^2 and $L_p = 1$ cd/m^2) and for each light spectra (blue, green, amber and red).

Figure 4 shows the reaction time as a function of background luminance for the four different light spectra at constant target contrast $C = 0.10$. There is a clear and statistically significant increase in reaction time with decreasing luminance for the red light. This increase in reaction time at lower luminance becomes smaller when the light spectrum shifts from longer wavelengths to shorter wavelengths. For the blue light no changes in reaction time were found between the two light levels.

3.1.2. The effects of light spectrum on reaction time

Figure 5 shows the reaction time as a function of light spectrum for different target contrasts and luminance levels. At the lower luminance level $L_p = 0.1$ cd/m^2 a significant difference in RT was found between different light spectra at both target contrasts ($C = 0.10$ and 0.15). Reaction time decreased when the light spectrum was shifting from long wavelength light (red) to short wavelength light (blue). Thus visual performance in terms of reaction time was better under the blue light than under the red light even though the photopically weighted luminance and contrasts were equal. When the luminance level was increased to $L_p = 1$ cd/m^2 no significant differences in RT were found between light spectra at the higher target contrast $C = 0.10$. At this luminance level at contrast $C = 0.05$ reaction time was significantly higher under the red light compared to the other light spectra, while no differences



a) *b)*

Fig. 5. Mean and standard deviation of reaction time (RT) plotted against light spectrum:

a) at background luminance L_p = 0.1 cd/m^2 and target contrasts C = 0.10 and C = 0.15; *b)* at background luminance L_p = 1 cd/m^2 and target contrasts C = 0.05 and C = 0.10

in reaction time where found between the other spectra.

3.2. Contrast threshold

Figure 6 shows the results of the contrast threshold measurements as a function of light spectrum at background luminance levels L_p = 0.1 cd/m^2 and L_p = 1 cd/m^2. CT was clearly increased when the background luminance was decreased. This was found for each light spectrum. The light spectrum had a major effect on contrast threshold at the lower luminance level, where CT was significantly decreased when the light spectrum was shifting from long wavelength light (red) to short wavelength light (blue). At the higher luminance level L_p = 1 cd/m^2 the effects of light spectrum became smaller. At this luminance level CT was significantly lower under the blue spectrum compared to the other light spectra, but there were no more differences in CT between the other light spectra.

3.3. Comparison of RT and CT behaviour

Both the reaction time and contrast threshold experiments showed a clear effect of background luminance on visual performance under mesopic conditions. Visual performance was clearly decreased with decreasing background luminance from 1 cd/m^2 to 0.1 cd/m^2. In these experiments the adaptation luminance was determined by the hemisphere background luminance and the target and background were of the same light spectrum (achromatic contrast). The experiments showed clear effects of light spectrum on visual performance at constant photopically weighted adaptation luminance. The magnitude of the effect of SPD on visual performance was dependent on the visual conditions (luminance level, target contrast). At the lower adaptation luminance the spectral effects on both RT and CT were clear while at the higher luminance the effects were diminished or disappeared. For the RT task the spectral effects decreased with increasing target contrast. The results confirmed that the photopic $V(\lambda)$ is not valid for assessing spectral luminous efficiency of peripheral vision under mesopic conditions. At low luminance levels in the mesopic region blue light is underestimated by the photopic $V(\lambda)$.

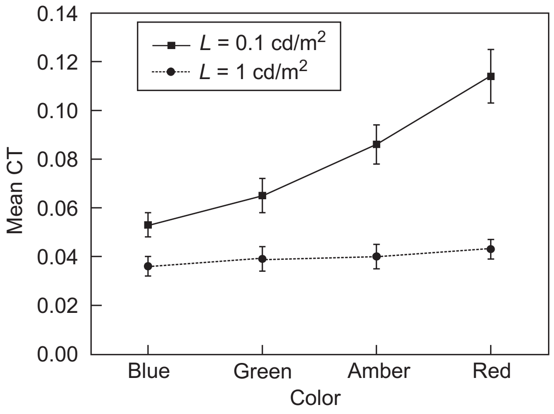


Fig. 6. Mean and standard deviation of contrast threshold plotted against light spectrum at two background luminance levels L_p = 0.1 cd/m^2 and L_p = 1 cd/m^2

4. Fitting the results to MOVE- and X-models

The reaction time and contrast threshold measurements of this work were carried out at equal photopically ($V(\lambda)$) weighted luminances under four different spectral lights. The photopic luminances and light source S/P-ratios were used to calculate the corresponding mesopic luminances with the MOVE- and X-models [12, 13], Table 4.

Due to the different spectral distributions of the light sources (coloured LEDs with narrow-band spectral bandwidths) the S/P-ratios of the four LEDs vary in a large extent. This correspondingly results in large differences in the calculated mesopic luminances. At the lower photopic luminance level (L_p = 0.1 cd/m^2) the mesopic luminances for the blue LED (high S/P-ratio) are significantly higher than the photopic value and the opposite is true for the red LED (low S/P-ratio). The differences in photopic and mesopic weighting become smaller with increasing light level. The X-model results in equal mesopic and photopic luminances at photopic luminance L_p = 1 cd/m^2, while the MOVE-model yields to different mesopic and photopic luminances also at this level. This is due to the different characteristics of the two models. The X-model assimilates to photopic dimensioning at L_p = 0.6 cd/m^2, while the MOVE-model calculates mesopic luminances up to about L_p = 10 cd/m^2 [12]. Figure 7 shows the ratios of mesopic-to-photopic luminances calculated with the two models as a function of photopic luminance.

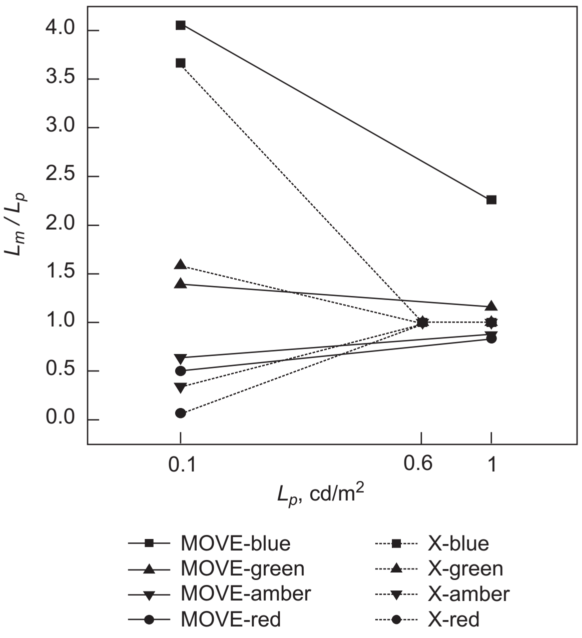


Fig. 7. Ratios of mesopic-to-photopic luminances L_m/L_p for the four light spectra (blue, green, amber, red LEDs) as a function of photopic luminance L_p. Mesopic luminances are calculated with the MOVE- and X-models [12, 13]

The RT and CT data plotted as a function of mesopic luminances are shown in Figures 8 and 9. If the two models were consistent in predicting mesopic spectral sensitivity they would give equal mesopic luminances for equal spectral conditions and consequently the RT and CT data would lie on one curve when plotted as a function of mesopic luminance. Figure 8 shows the RT data plotted as a function of mesopic luminance calculated using the MOVE- and X-models. For the target contrast C = 0.10, RT was measured at both photopic luminances using four different light spectra and there are consequently eight RT data points recorded at this contrast. At contrast C = 0.05, RT was measured at the higher photopic luminance (L_p = 1 cd/m^2) and at contrast C = 0.15 RT was measured at the lower photopic luminance (L_p = 0.1 cd/m^2), thus both contrasts yielding to four RT data points. Both models show a similar

Table 4

Mesopic luminances calculated using the MOVE- and X-models [12, 13] for the two photopic luminances (L_p = 1 and L_p = 0.1 cd/m^2) and the four spectral lights used in the experiments

Spectrum	**S/P-ratio**	**L_p = 1 cd/m^2**		**L_p = 0.1 cd/m^2**	
		L_{MOVE}	**L_X**	**L_{MOVE}**	**L_X**
blue	13.9	2.26	1	0.41	0.37
green	2.09	1.16	1	0.14	0.16
amber	0.239	0.87	1	0.06	0.03
red	0.0396	0.84	1	0.05	0.007

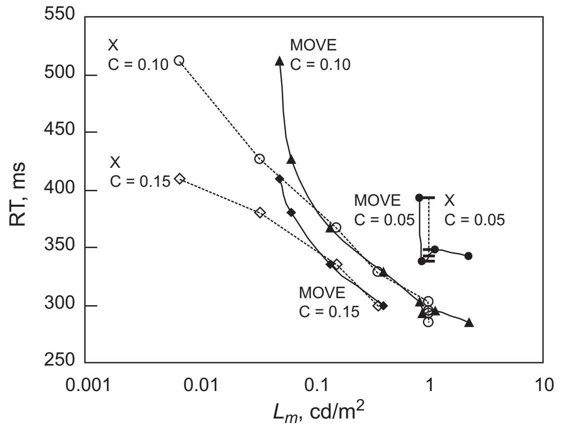


Fig. 8. Reaction time (RT) data plotted as a function of mesopic luminance L_m calculated using the MOVE- and X-models [12, 13]

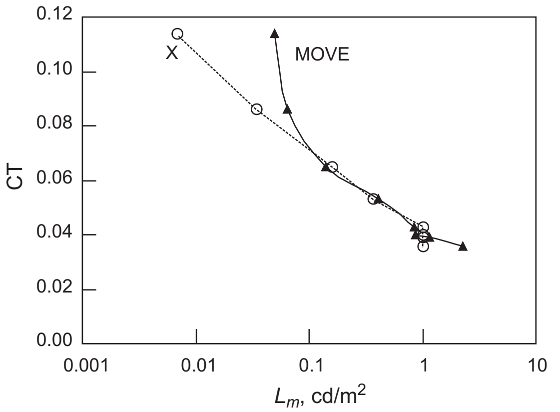


Fig. 9. Contrast threshold (CT) data plotted as a function of mesopic luminance L_m calculated using the MOVE- and X-models [12, 13]

trend in visual performance behaviour as a function of luminance; visual performance is increasing (RT decreasing) with increasing mesopic luminance. At contrast $C = 0.10$ (two curves in the middle), there are obvious differences in the two models' predictions at low light levels for long wavelength spectral lights (amber, red). Also, at the photopic level $L_p = 1$ cd/m^2 the model predictions deviate from each other. At this luminance the slight differences in RT data among the different light spectra are explained by the variation of mesopic luminances when using the MOVE-model, while the X-model gives equal mesopic luminances for the different light spectra. At target contrast $C = 0.05$ (two curves on the right), the differences in the model predictions become apparent as the X-model gives equal mesopic and photopic luminances and the MOVE-model mesopic luminances continue to predict the increase in RT with decreasing mesopic luminance. At target contrast $C = 0.15$ (two curves on the left), the deviations in the model predictions are again found for spectral lights with high long wavelength light (amber and red).

Figure 9 shows the contrast threshold data as a function of mesopic luminance. Both the X-model and the MOVE-model indicate a similar trend in CT behaviour as a function of luminance; visual performance in terms of contrast threshold becomes better with increasing mesopic luminance. As with the RT data differences between the model predictions can be seen at $L_p = 1$ cd/m^2 photopic luminance where the slight differences in CT data among the different light spectra are explained by the variation of mesopic luminances when using the MOVE-model. The X-model however gives equal mesopic luminances for the different light spectra at $L_p = 1$ cd/m^2. At the lower photopic luminance $L_p = 0.1$ cd/m^2 the MOVE- and X-model mesopic luminances for the blue and green lights are close to each other and the CT data as a function of mesopic luminance lie on the same curve. However, for the amber and red lights the CT curves predicted by the two models deviate from each other. Thus the MOVE- and X-models are not consistent in predicting contrast threshold behaviour for long wavelength spectral lights at low photopic levels. Also, the model predictions apparently start to deviate from each other at photopic luminances higher than 0.6 cd/m^2 which is the upper luminance limit of mesopic spectral sensitivity in the X-model.

It is obvious from the RT and CT data curves of Figures 8 and 9, that the predictions of the X-model and MOVE-model are not consistent. Firstly, the RT and CT data curves when plotted against mesopic luminance are different when using the two models. Secondly, the shapes of the RT and CT data curves when predicted by the two models are different from each other. In using the MOVE-model both the RT and CT data show a non-linear behaviour as a function of log-mesopic luminance. For the RT data this is found for all three target contrasts. This is not the case when using the X-model. The RT data curves for the X-model at the three different target contrasts have different shapes. Furthermore, the differences in visual performance (both CT and RT) at the higher photopic luminance 1 cd/m^2 are not accounted for by the X-model which results in discontinuation in the corresponding RT and CT data curves at the higher end of the luminance region. In using the X-model different behaviour of RT as a function of mesopic luminance at different target contrasts was found. This may be caused by the experimental conditions underlying the X-model as only high-contrast targets ($C = 0.70$) were used in establishing the X-model [13]. The experimental RT and CT data of this work indicated, that the spectral sensitivity changes are more pronounced at low visibility conditions (low luminance, low contrast). The inconsistency of the X-model to predict low-contrast RT data (3 various shapes of curves) may be caused by the X-models inaccuracy to assess spectral sensitivity for low contrast visual tasks.

It is premature to propose a model for mesopic photometry before the existing models are profoundly validated and their ability to assess mesopic responses in e.g. night-time driving conditions are further analysed. The use of visual performance data sets generated in this work in calculating mesopic luminances with the X- and MOVE-models indicated that these two models are not consistent in assessing mesopic spectral sensitivity. Based on the data of this work the MOVE-model is stated to perform better in predicting mesopic luminances. The X-model fails to predict a consistent RT and mesopic luminance behaviour for different target contrasts (3 shapes of RT data curves, Figure 8). Moreover, the measured differences in visual performance (RT and CT) at 1 cd/m^2 are not accounted for by the X-model. This is due to the upper luminance limit of 0.6 cd/m^2 of the X-model which obviously results in discontinuation of visual performance behaviour when plotted as a function of luminance. More data is, however, needed to further test the models and this work is continued within the CIE TC1-58 work.

5. Conclusions and discussion

The contrast threshold and reaction time data of this work showed a clear effect of background luminance on visual performance under mesopic conditions. There was a clear increase in visual performance when luminance was increased from $L_p = 0.1$ cd/m^2 to 1 cd/m^2. Both CT and RT data showed clear dependence of visual performance on light spectrum and the spectral effects were more pronounced at lower luminance level. The results indicated the change in spectral sensitivity towards short wavelengths with decreasing luminance level. The lower the target contrast in the RT experiments, the more pronounced were the spectral effects. The results showed that the magnitude of the effect of SPD on visual performance is influenced by the luminance and visual conditions. When the visual task becomes more and more difficult (lower luminance, lower contrast), the effect of spectrum will also become more significant. The results confirmed the inaccuracy of the photopic $V(\lambda)$) to predict spectral sensitivity of peripheral mesopic visual performance.

The task-dependency in the mesopic region refers to the visual task performance and spectral sensitivity being dependent on the specific visual task and the task parameters. Photometry is an attempt to describe the relationship between two illumination variables; the intensity and spectral composition of light. The performance-based mesopic models describe this relationship based on experiments of certain visual task performance. Although being based on certain visual tasks, the models should characterize the spectral sensitivity under other visual task conditions too to be generally applicable. The performance based mesopic models are based on the assumption that under fixed lighting and viewing conditions (target size, eccentricity etc.) the same visual performance level indicates same mesopic luminance. Thus different combinations of photopic luminance and lamp spectra will produce the same mesopic luminance if the task performance level is the same. This was chosen as the method to study and compare the X- and MOVE-models predictions.

In this work two recently introduced performance based mesopic models, the MOVE-model [12] and the X-model [13], were compared using newly established data sets on contrast threshold and reaction time. The models' ability to indicate same mesopic luminance at same visual performance levels were compared. Both models indicated the increase in visual performance with increasing mesopic luminance. The two models were not, however, consistent in predicting mesopic luminance and mesopic visual performance. This was seen as diverging RT and CT data curves when mesopic luminances were calculated with the two models. Further on the shapes of the visual performance data curves were not consistent between the two models. The differences between the models became clearer with decreasing visibility conditions, i.e. lower luminance, lower contrast. The reasons for the differences between the models may be the different parameter conditions under which the models' data were generated. The X-model is based on reaction time experiments at high target contrast ($C = 0.70$), which is quite high for the night time driving conditions. The MOVE-model experiments covered a range of target contrasts with particular attention paid to the low contrast range which is believed to be of relevance in night-time driving conditions. The target contrasts in the experiments of this work were relatively low ($C = 0.05$, 0.10, 0.15 in RT, at threshold in CT). The magnitude of the effect of SPD on visual performance depends on the visual conditions as also indicated by the visual performance data of this work. The inconsistency of the X-model to predict low-contrast RT data (3 various shapes of curves) may be caused by the X-models inaccuracy to assess spectral sensitivity for low contrast targets.

One major difference between the X- and MOVE-models is the transition point between mesopic and photopic regions. This is the photopic luminance at which X and x become unity. In the X-model, this point is at 0.6 cd/m^2. The MOVE-model calculates mesopic values for photopic luminances up to about 10 cd/m^2, where x becomes unity. The different transition points can be caused by the visual parameters used in the experiments when developing the models. The different transition points will result in differences when calculating mesopic luminances with the two models in the photopic luminance region 0.3-2 cd/m^2, which is the region of average road surface luminances given in the CEN, IESNA and Chinese road lighting recommendations [14, 15, 16]. In driving conditions, the luminances of the surrounding areas of the road can have values much lower than the road surface values. In estimating the spectral effects in road lighting conditions the luminances of the whole visual field should be considered, as the adaptation luminance is not determined by the road surface luminance alone. Thus the spectral effects of light in road and street lighting conditions may be even more pronounced when evaluated by the real adaptation luminance levels and not only by the road surface levels.

The comparison of the two mesopic models indicated that there are differences in the models' predictions and the MOVE-model is stated to perform better in predicting mesopic luminances. Based on the data presented here it is, however, premature to propose a model for mesopic photometry. It is obvious that more data should be established in order to validate and compare the existing mesopic models. In order for a mesopic model to be applicable in conditions encountered in night-time driving, the parameters used in establishing new data should include those typically found in night-time driving conditions. In the night time driving conditions, accidents are expected to increase due to poor visual conditions, such as low luminance, low target contrast and increasing target eccentricity [17]. In these conditions, the light spectrum significantly affects the visual performance of drivers and pedestrians. The acknowledged visual parameters should be decided according to real conditions of night time driving situation and need further investigation and discussion.

The special technical committee TC 1-58 of CIE is working on proposing a model for the basis of performance based mesopic photometry. The work of the TC1-58 includes the collection and analysis of existing and new performance based mesopic models. In analysing the models there should be a defined range of parameters which are relevant in e.g. night-time driving conditions and which should thus be selected for the basis of comparing the models. The use of the same parameter range internationally in validating and comparing the existing models would give a sound basis for future work.

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