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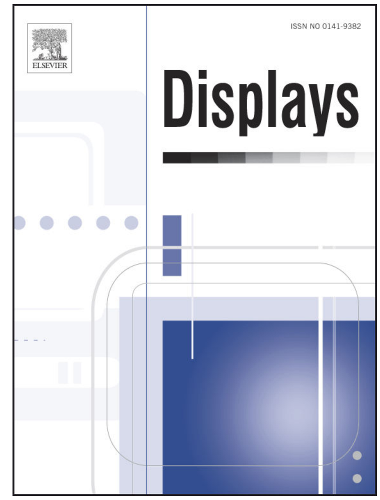

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The Influences of Tunnel Lighting Environment on Drivers' Peripheral Visual Performance during Transient Adaptation

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ABSTRACT

Highway tunnel lighting environments include sidewall, pavement, ceiling, etc., their surface luminance were affected by the distribution of luminous flux of the lamps. While driving through a highway tunnel, the driver needs to complete a series of visual tasks. The spatial distribution of the luminance and color on the road surface and sidewall, as well as the correlated color temperature, influence the driver's visual performance. The process of driving through a highway tunnel lighting environment was simulated in a laboratory where the luminance of the non-uniform visual environment was gradually decreased. The effects of the spatial distribution of the lighting environment parameters on a driver's visual performance was studied by testing each subject's reaction times and missed target rates. The tests showed that the spatial distribution of the lighting environment parameters significantly influences a driver's visual performance, and the effects on test subjects' peripheral visual performance are different in threshold, transition, and interior zones. The optimization of the spatial distribution of the lighting environment parameters can enhance traffic safety and energy saving of highway tunnel lighting.

Keywords: highway tunnel lighting environment, spatial distribution, transient adaptation, visual performance, traffic safety, energy saving.

1. Introduction

To ensure traffic safety and energy saving of highway tunnel lighting, artificial lighting methods have been discussed for many years. For example, a luminance reduction method which the luminance decrease in steps alone the threshold zone, transition zone, interior zone of a one way tunnel was recommended by Schreuder based on the relationships among the admissible luminance jump, the gradual decrease in luminance, and adaptation time according to experiments and measurements conducted in highway tunnels. The luminance reduction method, based on experiments on adaptation, was used to eliminate three types of effects while driving through a long highway tunnel: the disappearance of after-images (local adaptation), changes in induction, and changes in the size of the pupil [1]. Among these three types of effects, the disappearance of after-images (i.e. local adaptation) is caused by changes in the sensitivity of the visual system will result in delay or difficulty in identifying traffic targets, which has a significant inverse relationship with traffic safety. Meanwhile, the influence of adaptation to the surrounding luminance level on the detection thresholds of different objects was studied by Bourdy et al [2], who showed that the effects of adaptation can be substantial. Accordingly, the lighting method of luminance evolution along the tunnel was recommended in the Commission Internationale de l'Eclairage (CIE) technical report 88-2004. The method of stepwise reduction in luminance was proposed considering that undimmable high-intensity discharge lamps were used mainly in conventional tunnels [3–5]. However, a driver's transient blind period due to the stepwise reduction in luminance in the tunnel threshold zone was defined as visual oscillation, and the equivalent duration of visual oscillation was proposed for quantitative evaluation of the drivers' visual comfort by Du et al [6]. The present stopping sight distance at tunnel portals should be increased by 20–30 m to accommodate the general visual oscillation phenomenon. Safety evaluation of lighting on the basis of visual adaptation was studied by Ahman Mehri et al, based on the comparison of measured luminance and design values in different zones of a long tunnel in the Ilam province of Iran[7]. The study indicated that very low measured luminance results in black hole effects and reduces traffic safety. To reduces and control the natural lighting contribution in the threshold zone of the tunnel, a pre-tunnel structure was preferred to filter the natural light [8,9] or the high reflection concrete pavement[10] and sidewall[11] was preferred to improve the artificial lighting luminance, and so as to ease the sharp decrease of the luminance of road surface in the threshold zone. Therefore, it is important to study visual performance during transient adaptation, to optimize the tunnel lighting environment and improve the traffic safety of highway tunnels.

In order to alleviate the influence of dark adaptation caused by the change of luminance gradient on drivers, the visual adaptation problem in tunnel transition sections was studied by Huang (2013), who reported that the influence of different luminaires – i.e., with different spectral power distributions (SPDs) – on test subjects' reaction times vary. Additionally, the effects of correlated color temperature (CCT) on test subjects' visual adaptation at different luminance levels vary, indicating that a high value of CCT can decrease the time of visual adaptation at luminance levels below 50 cd/m^2. The effects of transient adaptation on the driver's visual performance were studied by He et al. [13] using a simulated highway tunnel in laboratory. That study showed that decreasing the luminance in steps increased mean reaction times and missed target rates, resulting in decreasing visual performance. The results indicated that a driver's spectral sensitivity is changed based on transient adaptation effects in the transition zones; that is, a driver's acuity and alertness are better for bluish than for reddish targets, and better for whitish than for greenish targets within tunnel transition and interior zones. At the same time, the impact of LED light color on dark adaptation of human vision in tunnel entrances were studied by Dong et al. [14] showed that the light color characteristics of LEDs significantly affected dark adaptation. Specifically, the better the color rendering and the lower the absence of blue light, the shorter the dark adaptation time. However, tunnel lighting environments, which include sidewall, pavement, road shoulder, ceiling, etc., and their surface luminance were affected by the distribution of luminous flux of the lamps. Those complex lighting environments are very different from the uniform visual environments in previous research and affect a driver's visual perception and safety in traffic. Therefore, it is important to study the influences of the visual environment on a driver’s visual performance during the process of transient adaptation.

When the driver drives through a highway tunnel, his fixation is primarily aimed at the front of the vehicle and his peripheral vision perceives mostly vehicles, pedestrians and other traffic targets, on both sides of the road. Fixation behavior is mainly realized through fovea vision, and the residual light in the eyes corresponds to its peripheral vision. Therefore, while driving, the perceptual characteristics of peripheral vision are very important for traffic safety. At the same time, as the perceptual background of peripheral vision, the feasible layout of road tunnel lighting environment has a significant impact on traffic safety. For the engineering aspects of tunnel lighting, the effects of different lighting distributions and varying reflectivity characteristics of road surface and sidewalls were studied based on a series of luminance calculations conducted by Westermann (1975). The calculations showed that a transverse lighting distribution can provide good lighting quality, and that highly reflective surfaces are the best solution to achieving traffic safety and energy savings in highway tunnel lighting. Therefore, the challenges that natural images pose for visual adaptation were studied by Fred Rieke and Michael Rudd (2009), who showed that the large range of input signals encountered in different regions of a scene renders global adaptation mechanisms (such as changes in pupil size) ineffective because of the limited range of physiological responses available for encoding the stimulus. The relevant visual field and the adaptation style were studied by Cengiz and Maksimainen [17,18], indicating that the target luminance and luminance distribution of the surrounding area affect periheral target detection, and that contrast threshold values did not differ between circular 10°and 20° fields of view under similar luminance distributions in nighttime driving. The influence of a dynamic highway tunnel lighting environment on driving safety was studied by He et al. (2017) based on the eye movement parameters of the driver. The results showed that eye movement parameters such as the position of the fixation point, the duration of the fixation, and changes in the rate of the increase in pupil diameter are more stable in a lighting environment with higher luminance on the tunnel sidewall.

As a driver drives through a highway tunnel, the influence of dynamic lighting on driver’s visual performance is similar to that of road lighting. Therefore, the lighting environments of access, threshold, transition, interior, and exit zones and the effects of different tunnel zones on a driver’s visual performance and driving state (especially the visual adaptation state) are very different. The lighting quality, including luminance and luminance uniformity of the road surface, is the key parameter in both road lighting and highway tunnel lighting in current lighting standards [3,19]. However, the lighting parameters of highway tunnel sidewalls in different tunnel zones might also have effects on driving safety. For instance, parameters of the highway sidewall may affect local adaptation, influencing the driver's visual performance in corresponding areas. In this study, the process of driving through a highway tunnel at a certain speed was simulated in a laboratory. Test subjects were asked to complete a series of visual tasks in the simulated visual environment to measure visual performance under the effects of transient adaptation. Meanwhile, the effects of spatial distribution of lighting environment parameters on a driver's visual performance could be obtained, along with specifications for standards makers to optimize the lighting environments of highway tunnels.

2. Material and methods

In this paper, the influence of different spatial distribution characteristics of light environment on the driver's visual performance was studied by measuring the driver's reaction times and missed targets rate of random targets, which appeared in the indoor simulation of the tunnel lighting environment where the luminance was decreased in steps. The hardware of the experimental setup is mainly includes the uniform background luminaire (L-FIELDS E 44W LED840 M600Q LDE, Zumtobel), the projector (BenQ 1007), the screen (approximately Lambertian surface) et al. The specific layout of the experimental setup is shown in Fig. 1. The software system includes LabVIEW program platform, projection fusion software (Immersive Calibration PRO v2.3) and DALI lighting control system for controlling background and target presentation.

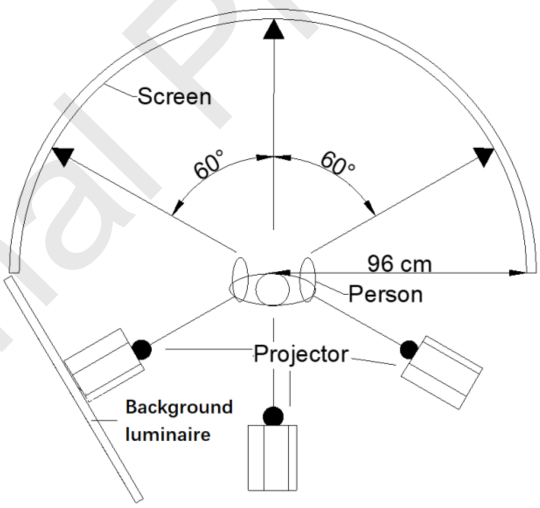


Fig. 1. Experimental setup from top view.

The light environment was simulated when the driver driving through a highway tunnel at 80km / h. According to the China highway tunnel lighting standards[4], the specific luminance and duration parameters of the simulated light environment are shown in the Tab. 1.

Tab. 1. The design parameters of simulation light environment.

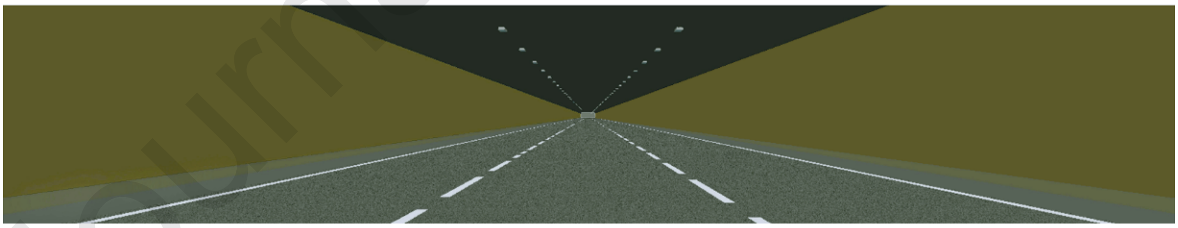
Luminance (cd/m^2)	5000	175	87.5	26.5	8.75	4	4
Simulated	Access	Threshold	Threshold	Transition	Transition	Transition	Interior

lighting zones	zone	zone	zone	zone	zone	zone	zone
Duration	180	1.9	1.9	3.2	4	6	6
Background	LED	White	White	(a)-(f)	(a)-(f)	(a)-(f)	(a)-(f)
Targets	--	T1	T2	T3, T4	T5, T6	T7-T9	T10-T17

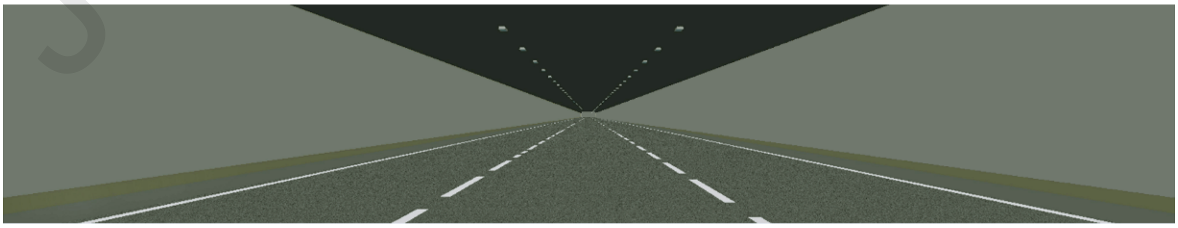
The construction of a stepwise luminance lighting environment, visual targets and the test procedure are introduced below.

2.1 The construction of a stepwise luminance lighting environment

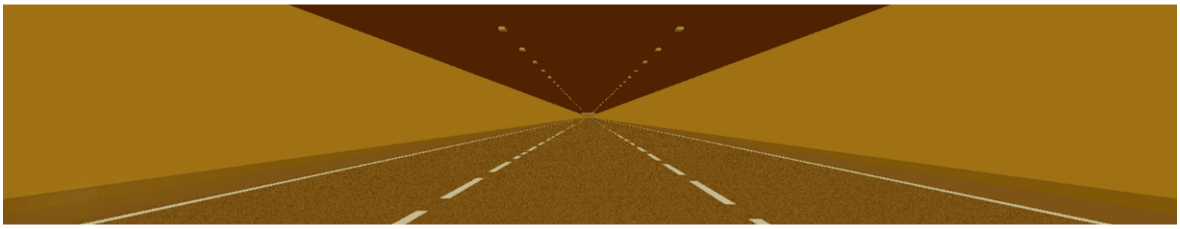
The standard white visual environment with luminance levels (175, 87.5 cd/m^2) and six kinds of visual environments with three different luminance levels (26.25, 8.75, and 4 cd/m^2) were selected for both background and target. For each visual environment, luminance values were measured using spectroradiometers (Konica-Minolta CS 2000) focused on both the road surface and the sidewall of a non-uniform background, where the spectroradiometers were in the position of the test subjects, as in Fig. 1. A large screen, illuminated by the three projectors (BenQ 1007), was used to create the visual environment as shown in Fig. 4. The spatial distribution of the lighting environment parameters (SDLEPs) such as the LOR (the luminance of the road surface), LOS (the luminance of the sidewall), COS (the color of the sidewall), and CCT (the correlated colour temperature) of the visual environment were selected. The six types of visual environments were obtained based on combinations of these four lighting environment parameters. For instance, in the visual environment shown in Fig. 2(a), the COS is yellow, the CCT is 5900 K, and the luminance ratio of the sidewall and the road surface (LROSR) is 1:1. Meanwhile, only the COS and the LROSR were changed into gray and 1:2, respectively, in the visual environment as shown in Fig. 2(b) with the comparison of the visual environment as shown in Fig. 2(a). The LROSR was a combination of SDLEPs with different LOR and LOS, where the LOR is the same for these four kinds of visual environments.



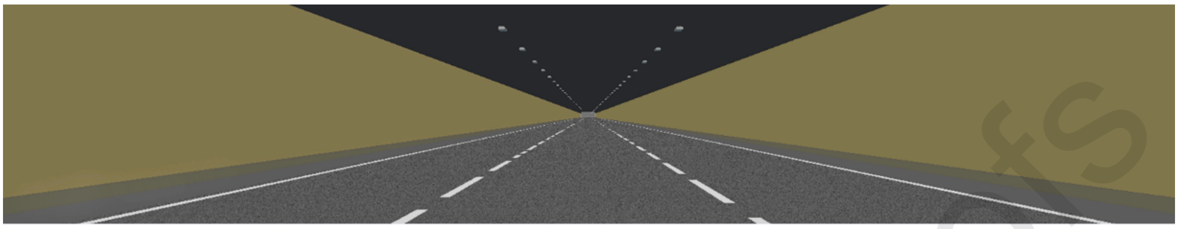
(a) COS, yellow; CCT, 5900 K; LROSR, 1:1



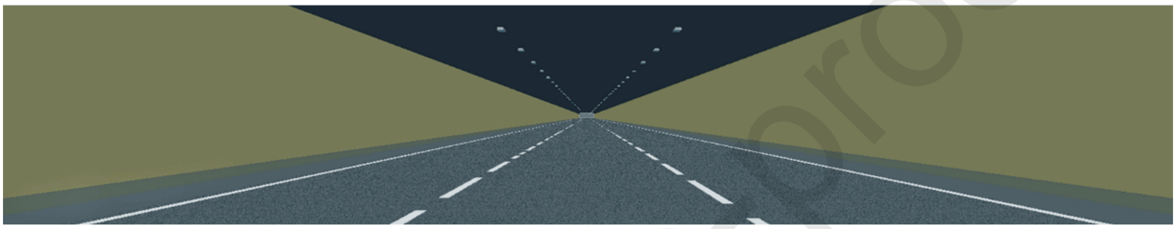
(b) COS, gray; CCT, 5900 K; LROSR, 2:1



(c) COS, yellow; CCT, 2400 K; LROSR, 2:1



(d) COS, yellow; CCT, 5900 K; LROSR, 2:1



(e) COS, yellow; CCT, 9000 K; LROSR, 2:1

(f) COS, yellow; CCT, 5900 K; LROSR, 4:1

Fig. 2. Six kinds of visual environment with a combination of different SDLEPs.

2.2 Visual targets

In the experiment, the 1.5 ° achromatic disk was used to simulate the vehicle, pedestrian, traffic sign and other targets that the driver may encounter when driving through the highway tunnel. Target location is (-30°, 0°), (-10°, 0°), (0°, 0°), (10°, 0°), (30°, 0°), (0°, 15°), (0°, 7°). The target location distribution is shown in Fig. 3. The shape of each target was a disk, and each target's contrast was 0.3 at each luminance level and is slightly higher than the minimum required perceived contrast 0.28. The contrast was calculated using Eq. (1) as follows:

$$C = \frac{L_t - L_b}{L_b} \tag{1}$$

where C is the contrast, L_b is the background luminance, and L_t is the target luminance.

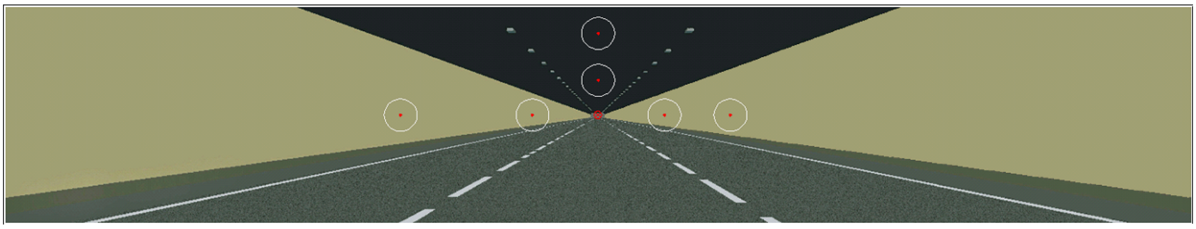


Fig. 3. Screen size and target locations in terms of horizontal and vertical eccentricities.

Limited by the interval of luminance occurrence in each zones, the target occurrence location in this experiment is randomly distributed, however, the target occurrence time is arranged in combination with the duration of each zones. The relationship between the occurrence time of target T1-T8 and luminance switching time is shown in Tab. 2. No luminance changes occurred for targets T9–T17.

Tab. 2. Times between the luminance changes and the appearances of targets T1–T8.

Target no.	T1	T2	T3	T4	T5	T6	T7	T8
Time (ms)	0	465	0	1851	0	1540	0	1426

2.3 Test procedure

Ten people were selected as the test subjects, including five men and five women. The test subjects had normal vision or were corrected to normal vision. The mean age of these tests subjects was 27 years, with a standard deviation of 2.14 years. Their color vision was tested as normal using an Ishihara color vision test. Information on the test subjects is provided in Tab. 3.

Tab. 3. Information about the 10 test subjects.

Name	Age	Gender	Vision	Driving experience	Nationality
A	27	Male	Corrected with optical lens	No	China
B	24	Female	Corrected with optical lens	No	China
C	27	Female	Normal	No	China
D	28	Female	Corrected with optical lens	No	China
E	26	Male	Corrected with optical lens	No	China
F	26	Female	Corrected with optical lens	No	China
G	27	Male	Corrected with optical lens	No	China
H	24	Female	Normal	1 year	Thailand
I	24	Male	Corrected with optical lens	1 year	China
J	32	Male	Corrected with contact lens	14 years	Finland

The complete experiment consisted of six subroutines to test all six visual environments. The tests involving the six types of visual environments began with white backgrounds as the luminance decreased from 5000 to 175 cd/m^2 and changed into the respective visual environments at 26.25, 8.75, and 4 cd/m^2 because the luminous flux of the projector for each color was limited which is shown in Table 1. For each test subject, the same six subroutines were repeated after a 10 min break. The test procedure is shown in Fig. 4 and Fig. 5.

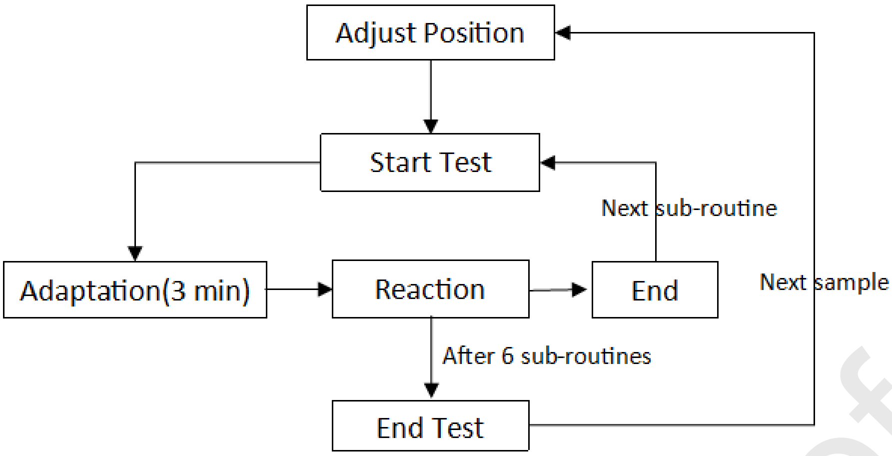
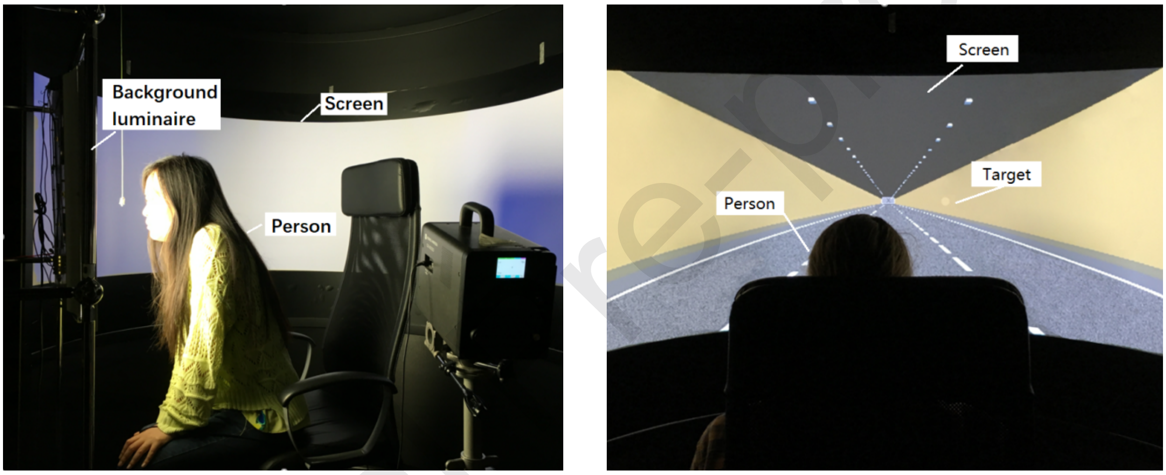


Fig. 4. Test process



(a) Adaptation (b) Reaction

Fig. 5. Test process of the actual test situation

The test consists of two parts: adaptation stage and reaction stage. The adaptation stage is mainly to make the tested subjects adapt to the environment of 5000 cd/m^2 for 3 minutes. During the position adjustment stage, the test subjects were asked to adjust the height of their eyes to the level of the center of the screen, which was used as the fixation point. After the adaptation, the LED luminaire was turned off before the reaction time test started. During the reaction stage, the test subjects were asked to fix their gaze at the center of the screen, and use their peripheral vision to detect and react with the visual targets in the process of transient adaptation.

3. Results

Through 120 tests, 1800 results including the reaction times and the missed targets were obtained during the process of transient adaptation. The mean reaction times and associated standard deviations and the missed target rates are shown in Appendix A. Among them, the test results of one subject's was discarded because the target loss rate was too high to 72%. For the other nine subjects, the test results of targets T1 and T2 were ignored due to they were appearing at the same background (a result of the limitation of the experimental devices). The test results of T3, T6, T8, T12, T14, and T17 in visual environments (a), (c), and (e), and the test results of T5, T8, T10, T12, T13, T15, and T17 in visual environments (b), (d), and (f) were ignored due to the target appearing in the vault (which is inconsistent with the actual traffic target). The 918 results were selected according to the purpose of the test, mainly to detect the effects of a non-uniform visual environment on the driver's visual performance.

For tunnel zones and target locations, the effects of SDLEPs on the reaction times and missed targets were analyzed through an analysis of variance (ANOVA), which includes six kinds of visual environments. Table 4 shows the results of the ANOVA.

Tab. 4. The ANOVA results of the missed target rate and the mean reaction time.

Source of variation	Reaction time		Missed target rate	
	F	P	F	P
SDLEP	**5.98**	**0.000**	**11.52**	**0.000**
Tunnel zones	**12.13**	**0.000**	0.09	0.757
Target location	**7.69**	**0.000**	1.53	0.204
SDLEP*Tunnel zones	1.15	0.331	1.469	0.222
SDLEP* Target location	**2.85**	**0.000**	**3.05**	**0.000**
Tunnel zones*Target location	**16.47**	**0.010**	0.39	0.861
SDLEP*Tunnel zones*Target location	**7.43**	**0.000**	**3.14**	**0.003**

The significant differences are indicated in bold which the significance level was 0.05.

Table 4 shows that the effects of the tunnel zones, target locations, and SDLEPs on the reaction times are significantly different, the effects of the SDLEPs on the missed target rates are significantly different. However, the interaction effects of the SDLEP and Target location, the Tunnel zones and Target location, the SDLEP and Tunnel zones and Target location on the reaction times are significantly different, the interaction effects of the SDLEP and Target location. The SDLEPs and Tunnel zones and Target location on the missed target rates are significantly different.

Therefore, the effects of adaptation time on visual performance was analyzed in condition (d) (COS, yellow; CCT, 5900 K; LROSR, 2:1). The effects of SDLEPs on the visual performance was analyzed in the threshold and transition zones and within the interior zones according to the transient adaptation conditions, which were mainly based on the mean reaction times of the targets.

3.1 Statistical analysis of adaptation time

For adaptation time and target locations, the effects of SDLEPs on the reaction times and missed targets were analyzed through an analysis of variance (ANOVA). The ANOVA includes six kinds of visual environments. Tab. 5 shows the results of the ANOVA.

Tab. 5. The ANOVA results of the missed target rate and the mean reaction time.

Source of variation	Reaction time	Missed target rate
	P	P
Adaptation time	**0.001**	**0.010**
Target location	**0.017**	**0.032**
SDLEP	**0.027**	**<0.001**

The significance level was 0.05. The significant differences are indicated in bold.

Based on the results of the test subjects, the mean reaction times of six different visual environments were obtained for the target number. The mean reaction times and missed target rates based on the target number and the luminance level in condition (d) (COS, yellow; CCT, 5900 K; LROSR, 2:1) are shown in Fig. 6.

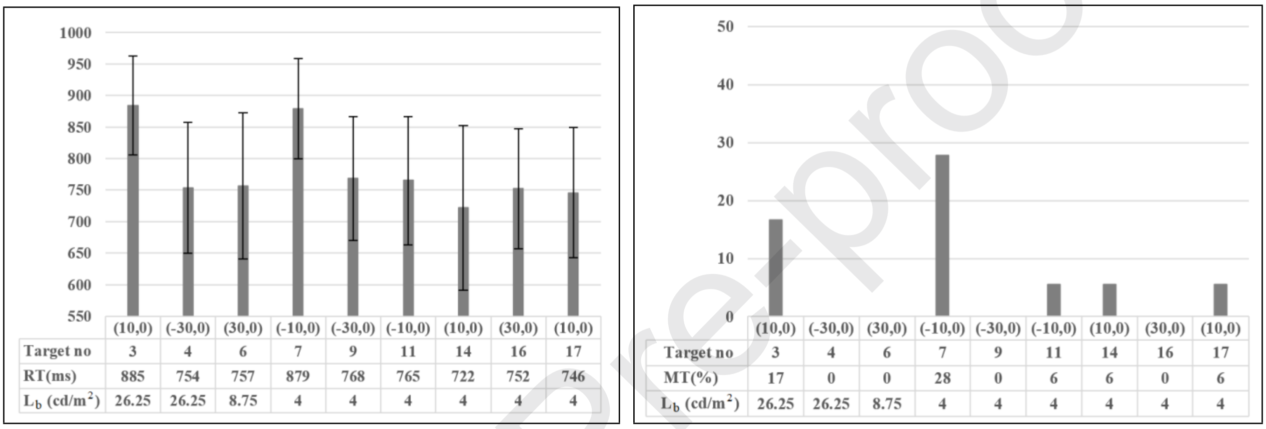


Fig. 6. Mean reaction time (RT) (ms) and missed targets (MT) (%) rate as a function of the target number. Note: The error bars indicate the standard deviations.

Based on the post hoc mean reaction time analysis, the mean reaction time and missed targets rate of the target number were divided into two homogeneous subsets on Fig. 6. The first subset included T3 (885 ms) and T7 (879 ms), whereas the second subset included the remaining targets: T4 (754 ms), T6 (757 ms), and T9, T11, T14, T16, T17 (768, 765, 722, 752, and 746 ms, respectively). The mean reaction time for the first subset (882 ms) was significantly higher than that of the second subset (752 ms). Meanwhile, the missed target rates of the first subset included T3 (17%) and T7 (28 %), whereas the second subset included the targets: T4 (0), T6 (0), and T9, T11, T14, T16, T17 (0, 6%, 6%, 0, and 6%, respectively). The mean missed target rates for the first subset (22.5 %) was significantly higher than that of the second subset (2.6 %).

3.2 Statistical analysis in threshold and transition zones

The effects of target locations and SDLEPs on the reaction times and missed targets were analyzed through an analysis of variance (ANOVA) in threshold and transition zones. Tab. 6 indicates that the effects of the target locations on the reaction times are significantly different, the effects of the SDLEPs on the target locations and missed target rates are significantly different.

Tab. 6. The ANOVA results of the missed target rate and the mean reaction time in threshold and transition zones.

Source of variation	Reaction time	Missed target rate
	P	P
Target location	**<0.001**	**<0.001**
SDLEP	**0.048**	**<0.001**

The significant differences are indicated in bold which the significance level was 0.05.

Based on the results of the test subjects, the mean reaction times of six different visual environments were obtained for the target number. The mean reaction times and missed target rates based on the target number, location and the SDLEPs are shown in Fig. 7 and Fig. 8.

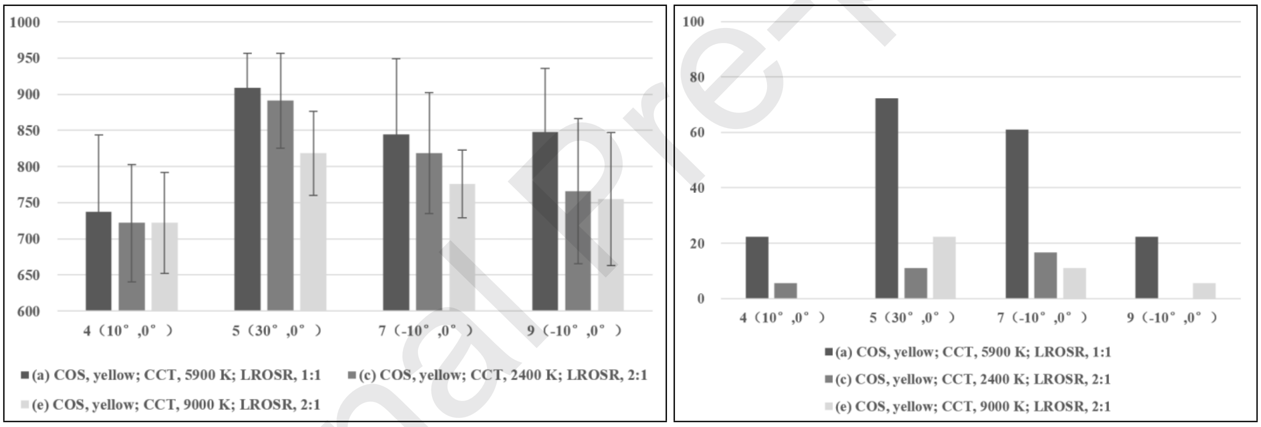


Fig. 7. Mean reaction time (ms) and missed targets rate (%) as a function of the target number.
Note: The error bars indicate the standard deviations.

Based on Fig. 7, the mean reaction times and missed target rates of T5 (873 ms, 35%) and T7(813 ms, 30%) was higher than that of T4 (727 ms, 9%), T9 (790 ms, 9%) due to the effects of the transient adaptation. For the influence of SDLEPs, the mean reaction times and missed target rates of targets in lighting environment (a) (COS, yellow; CCT, 5900 K; LROSR, 1:1) is 835 ms and 44% respectively, which is significant higher than that in lighting environment (c (COS, yellow; CCT, 2400 K; LROSR, 2:1)) (799 ms, 8%) and (e (COS, yellow; CCT, 9000 K; LROSR, 2:1)) (768 ms, 10%).

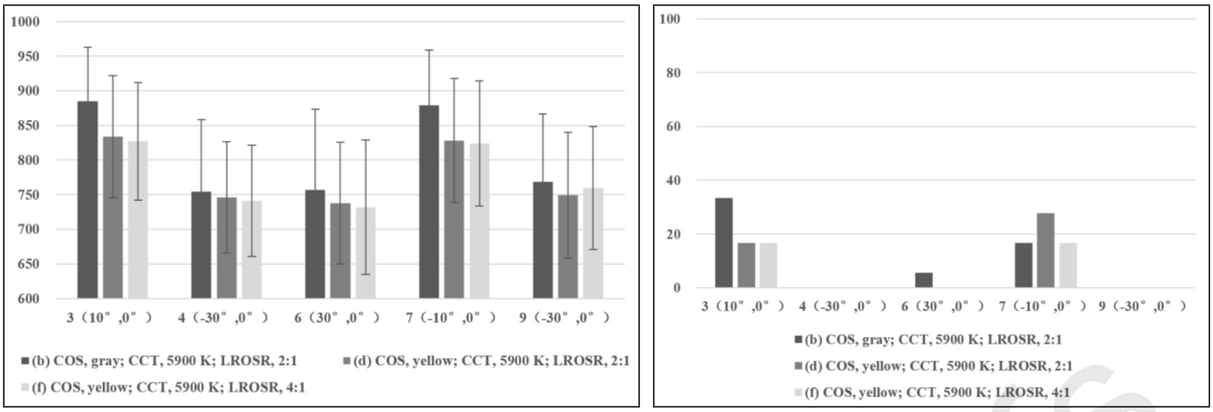


Fig. 8. Mean reaction time (ms) and missed targets rate (%) as a function of the target number.

Based on Fig. 8, the mean reaction times and missed target rates of T3 (848 ms, 22%) and T7(844 ms, 20%) was higher than that of T4 (747 ms, 0), T6 (742 ms, 2%) , T9 (759 ms, 0) due to the effects of the transient adaptation. For the influence of SDLEPs, the mean reaction times and missed target rates of targets in lighting environment (b) (COS, gray; CCT, 5900 K; LROSR, 2:1) is 809 ms and 11% respectively, which is significantly higher than that in lighting environment (d) (779 ms, 9%) and (f) (777 ms, 7%). However, for targets T9, the mean reaction times and missed target rates in lighting environment (f) (COS, yellow; CCT, 5900 K; LROSR, 4:1) is slightly higher than that in lighting environment (d) (COS, yellow; CCT, 5900 K; LROSR, 2:1).

3.3 Statistical analysis of SDLEP in the interior zone

The effects of target locations and SDLEPs on the reaction times and missed targets were analyzed through an analysis of variance (ANOVA) in interior zone. Tab. 7 indicates that the effects of the SDLEPs on the target locations and missed target rates are significantly different.

Tab. 7. The ANOVA results of the missed target rate and the mean reaction time in interior zones.

Source of variation	Reaction time	Missed target rate
	P	P
Target location	**0.023**	0.055
SDLEP	**<0.001**	**<0.001**

The significant differences are indicated in bold which the significance level was 0.05.

The mean reaction times of targets appearing in the interior zone in these six visual environments are shown in Fig. 9.

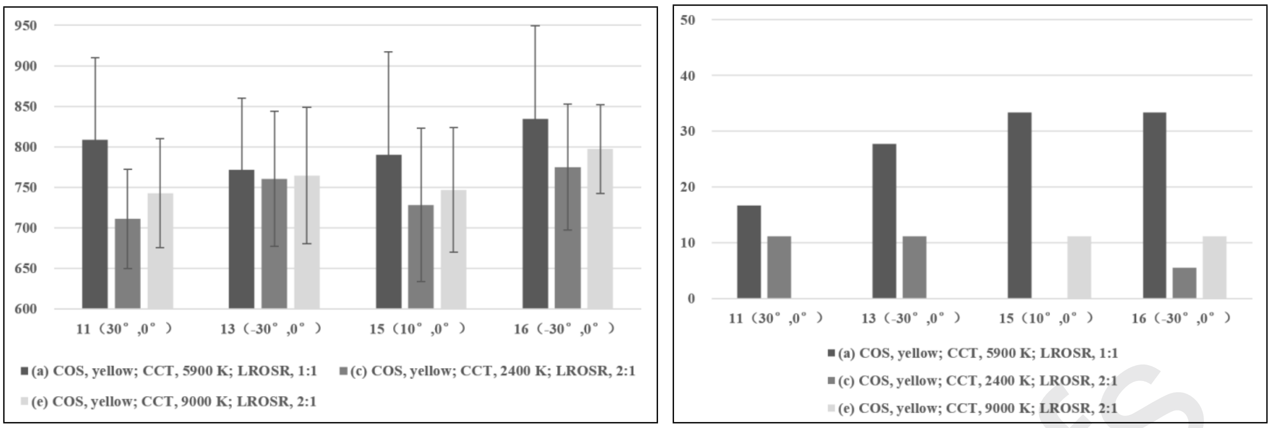


Fig 9. Mean reaction time (ms) and missed targets rate (%) as a function of the target number.

For the influence of SDLEPs, the mean reaction times and missed target rates of targets in lighting environment (a) (COS, yellow; CCT, 5900 K; LROSR, 1:1) is 801 ms and 28% respectively, which are significantly higher than those in lighting environments (c) (COS, yellow; CCT, 2400 K; LROSR, 2:1) (744 ms, 7%) and (e) (COS, yellow; CCT, 9000 K; LROSR, 2:1) (763 ms, 6%). Meanwhile, the mean reaction times and missed target rates of targets in lighting environment (c) (COS, yellow; CCT, 2400 K; LROSR, 2:1) is slightly higher than that in lighting environment (e) (COS, yellow; CCT, 9000 K; LROSR, 2:1).

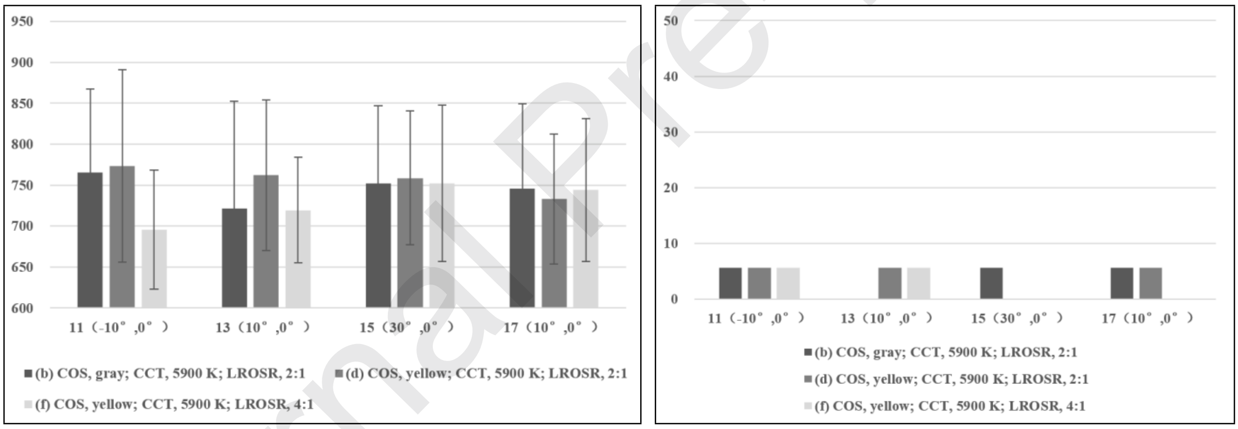


Fig. 10. Mean reaction time (ms) and missed targets rate (%) as a function of the target number.

Fig. 10 shows that the mean reaction times of targets in lighting environment (d) (COS, yellow; CCT, 5900 K; LROSR, 2:1) is 757 ms, which is slightly higher than that in lighting environment (b) (746 ms) and (f) (728 ms). Meanwhile, the mean reaction times of targets in lighting environment (b) (COS, grey; CCT, 5900 K; LROSR, 2:1) is slightly higher than that in lighting environment (f) (COS, yellow; CCT, 5900 K; LROSR, 4:1). The missed target rates of targets in lighting environment (b), (d) and (f) is lower and there is not much difference.

4. Discussion

For traffic safety and energy saving of highway tunnel lighting, luminance reduction methods [3–5] in different tunnel zones have been recommended to reduce the luminance transition when driving from the access zones to the parting zones, due to the undimmable high-intensity discharge lamps that were mainly used in conventional tunnels. However, with the effects of transient adaptation, the mean reaction time of the test subjects was significantly higher in the test with a non-uniform background. This indicates that the driver's visual performance was decreased when applying the step-by-step methods. This is consistent with the results achieved in a study of the effects of transient adaptation on a driver's visual performance under highway tunnel lighting when the test subjects were in front of a uniform background (He et al., 2017). When a driver drives through a highway tunnel, the effects of transient adaptation will result in a transient blind, which is defined as visual oscillation by Du (2014). It can be concluded that the main cause of visual oscillation behavior is the decrease of luminance gradient when drivers drive through a highway tunnel. However, the advanced light-emitting diode (LED) technologies with stepless dimming system have made gradual reduction of illuminance possible. For example, LED lights were used in the Shiratori tunnel on Japanese expressways to achieve a luminance uniformity greater than 0.9 [20]. Therefore, the effects of transient adaptation on a driver's visual performance should be considered in the design of the tunnel lighting, and it is important to ease up on the luminance reduction methods to avoid the effects of a transient adaptation.

As regards the effects of the SDLEPs, Fig. 7 indicates that the mean reaction time of the test subjects decreased with an increase in the LROSR, and the mean reaction time of the test subjects decreased slightly while the CCT changed from 2400 K to 9000 K in the threshold and transition zones. Fig. 8 indicates that the mean reaction time of the test subjects is lower when the COS is yellow than when the COS is gray, and the mean reaction time of the test subjects decreased slightly with an increase in the LROSR (from 2:1 to 4:1). Fig. 9 indicates that the mean reaction time of the test subjects decreased with an increase in the LROSR, and the mean reaction time of the test subjects increased slightly while the CCT changed from 2400 K to 9000 K in the interior zone. Fig. 10 indicates that the mean reaction time of the test subjects is higher when the COS is yellow than when the COS is gray, whereas increasing the LROSR from 2:1 to 4:1 can obtain the lowest mean reaction time. This indicates that a higher LROSR can increase the driver's visual performance in all of the threshold, transition and interior zones, whereas increasing the LROSR from 1:1 to 2:1 was found to be more effective compared to the increase of the LROSR from 2:1 to 4:1, and the shortest reaction times were found when LROSR is 4:1 in the threshold and transition zones. Meanwhile, it is evident that a highway tunnel with a yellow sidewall can increase the visual performance of the driver compared to one with gray sidewalls in the threshold and transition zones. But in the interior zone, the highway tunnel with a yellow sidewall would decrease the visual performance of the driver than one with a gray sidewall. Regarding the effects of the CCTs, the visual performance in the threshold and transition zones of the test subjects increased slightly when the CCT changed from 2400 K to 9000 K, whereas the visual performance of the test subjects in the interior zone decreased slightly with the same change in CCT.

The increase of the improvement of the visual performance of the tested subjects is directly proportional to the LROSR of the highway tunnel, whether it is the transition or the interior zones. According to CIE technical report 88-2004, the recommended suggestion is that the tunnel surface reflectance has a significant impact on the effectiveness of light fixtures in meeting the lighting design criteria. The IESNA RP22-11 standards recommended that treated wall surfaces be of an easily maintainable, highly reflective, non-specular material having an initial reflectance of at least 50 percent. And JTG/T D70/02–01-2014 standards recommended that the high reflectivity sidewall material should be used with a height of 2 m. The purpose of the above standards is to improve the road surface luminance by improving the sidewall reflectance. However, through the research of this paper, it is found that the improvement of the sidewall luminance can also improve the driver's detection probability of traffic events on both sides of the road, thus improving traffic safety. At the same time, the reflectivity of the road surface is generally far lower than that of the sidewall. While it is of limited value to improve the luminance of the road surface by increasing the distribution of the luminous flux on the road surface, we suggest an appropriate allocation of luminous flux to the sidewall surface, which can greatly improve both the luminance of the sidewall surface and traffic safety.

The experimentation regarding visual performance in the non-uniform visual background of the threshold transition or interior zones of the highway tunnel, we found that the influence of CCT and COS on visual performance differs across the various tunnel zones. Combined with the experimental results, we think that the reason for the above phenomenon may be the essential difference between the lighting characteristics of the two lighting zones; that is, the threshold and transition zones are dominated by the change of luminance gradient, and the tested subjects must constantly adjust the visual system to carry out dark adaptation. In the interior zone, the tested subjects basically complete the dark adaptation, mainly focusing on the visual tasks under low luminance or mesopic luminance. In this test, visual performance can be improved by choosing a suitable visual environment in different zones. However, highway tunnel lighting standards [3–5] do not provide any recommendations for SDLEPs regarding highway tunnel lighting. Therefore, further study should focus on the results indicating that visual performance can be improved through the adoption of suitable SDLEPs.

When driving through a highway tunnel, the driver's eye movement parameters change continuously to complete a series of visual tasks [21]. The visual performance is the combined result of foveal and peripheral perceptions per glimpse and saccadic eye movements [22]. According to the characteristics of the visual objects, including vehicle, pedestrians, roadway, and traffic signs in a highway tunnel, the visual field was divided into a safe area and an unsafe area by He et al. (2017). This indicated that drivers can distinguish neighboring vehicles and other traffic signs when their fixation point is focused on a safe area located in the center of their visual field. In this paper, the test subjects were asked to fixate at the center of the screen and use their peripheral vision to detect and react to the visual targets during the process of transient adaptation in the test. This is based on the hypothesis that drivers will perceive a target using their peripheral vision first, and then react or detect the target using their foveal vision when driving through a highway tunnel. Therefore, whether the hypothesis of this paper is consistent with the driver's preview-perception process remains to be determined through further studies. Meanwhile, the effects of target location on drivers' peripheral visual performance with different SDLEPs is in need of further study.

Meanwhile, for this test, influencing factors such as S/P ratio (ratio of the luminous output of a light source evaluated according to the CIE scotopic spectral luminous efficiency function to the luminous output evaluated according to the CIE photopic spectral luminous efficiency function) and mesopic luminance [23] may also have an impact on the visual performance of the tested subjects, especially in the interior zone of highway tunnel lighting, but is limited to the content of the article; this needs further study. The mean age of the ten test subjects was 27, and the standard deviation was 2.14. The test subjects have relatively mature visual system [24]. The technical report also showed that visual performance decreases as the age of the test subjects increases. An effective ambience created through lighting for older people was studied by Kuijsters et al. (2015). Their results, based on a questionnaire regarding the driving atmosphere by younger and older participants, differed significantly. Therefore, further study should focus on the effects of SDLEPs on the different types of test subjects.

5. Conclusions

The luminance was decreased in steps according to the IESNA RP22-11 and JTG/T D70/02–01-2014 standards, consistent with the luminance evolution curves presented in the CIE 88–2004 technical report. The results of visual performance experiments conducted in a non-uniform visual environment were consistent with the conclusions found under a uniform visual environment. This indicates that decreasing the luminance in steps increases the mean reaction times and decreases the driver's visual performance. Although these modifications can reduce the effects of adaptation on a driver's visual performance and eliminate the effects of the disappearance of after-images when driving through a long highway tunnel, the method for achieving a stepwise decrease in luminance should be optimized for application to highway tunnel lighting with the implementation of LED products.

Regarding the effects of SDLEPs, the mean reaction time of the test subjects decreased with an increase in the LROSR in all of the threshold, transition and interior zones, and the influence of CCT and the COS on visual performance varies in different tunnel zones. However, the design of SDLEPs was not recommended in previous highway tunnel lighting standards. Therefore, it is necessary to improve the driver's visual performance by optimizing the spatial distribution of the lighting environment parameters in the design of a highway tunnel. Further study should focus on the application of the results indicating that the visual performance can be improved through the adoption of suitable SDLEPs.

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Appendix A. Mean reaction times (ms) and the associated standard deviations and missed target rates.

Target no.	a	c	e	Target no.	b	d	f
3. (0°,15°) R.T	--	--	--	3. (10°,0°) R.T	885	834	827
S.D.	--	--	--	S.D.	79	88	85
M.R (%)	--	--	--	M.R (%)	6	3	3
4. (10°,0°) R.T	738	722	722	4. (-10°,0°) R.T	754	746	741
S.D.	106	81	70	S.D.	104	80	81
M.R (%)	4	1	0	M.R (%)	0	0	0
5. (30°,0°) R.T	909	891	819	5. (0°,7°) R.T	--	--	--
S.D.	48	66	58	S.D.	--	--	--
M.R (%)	13	2	4	M.R (%)	--	--	--
6. (0°,15°) R.T	--	--	--	6. (30°,0°) R.T	757	737	732
S.D.	--	--	--	S.D.	116	88	97
M.R (%)	--	--	--	M.R (%)	1	0	0
7. (-30°,0°) R.T	844	818	776	7. (-30°,0°) R.T	879	828	824
S.D.	105	84	47	S.D.	79	90	90
M.R (%)	11	3	2	M.R (%)	3	5	3
8. (0°,7°) R.T	--	--	--	8. (0°,15°) R.T	--	--	--
S.D.	--	--	--	S.D.	--	--	--
M.R (%)	--	--	--	M.R (%)	--	--	--
9. (-10°,0°) R.T	848	766	755	9. (-30°,0°) R.T	768	749	760
S.D.	88	100	92	S.D.	99	91	89
M.R (%)	4	0	1	M.R (%)	0	0	0
10. (0°,15°) R.T	--	--	--	10. (0°,15°) R.T	--	--	--
S.D.	--	--	--	S.D.	--	--	--
M.R (%)	--	--	--	M.R (%)	--	--	--
11. (30°,0°) R.T	809	711	743	11. (-10°,0°) R.T	765	774	695
S.D.	101	61	67	S.D.	102	118	73
M.R (%)	3	2	0	M.R (%)	1	1	1
12. (0°,7°) R.T	--	--	--	12. (0°,15°) R.T	--	--	--
S.D.	--	--	--	S.D.	--	--	--
M.R (%)	--	--	--	M.R (%)	--	--	--
13. (-30°,0°) R.T	772	761	764	13. (10°,0°) R.T	722	762	719
S.D.	88	83	84	S.D.	130	92	64
M.R (%)	5	2	0	M.R (%)	0	1	1
14. (0°,15°) R.T	--	--	--	14. (0°,15°) R.T	--	--	--
S.D.	--	--	--	S.D.	--	--	--
M.R (%)	--	--	--	M.R (%)	--	--	--
15. (10°,0°) R.T	790	728	747	15. (30°,0°) R.T	752	759	752
S.D.	128	94	77	S.D.	95	82	95
M.R (%)	6	0	2	M.R (%)	1	0	0
16. (-30°,0°) R.T	834	775	797	16. (0°,7°) R.T	--	--	--
S.D.	115	78	55	S.D.	--	--	--
M.R (%)	6	1	2	M.R (%)	--	--	--
17. (0°,7°) R.T	--	--	--	17. (10°,0°) R.T	746	733	744

S.D.	--	--	--	S.D.	103	79	87
M.R (%)	--	--	--	M.R (%)	1	1	0

R.T. = mean reaction time, S.D. = standard deviation, M.R. (%) = mean missed target rate.

Highlights

1. The effects of transient adaptation on peripheral vision in non-uniform visual environment were investigated.

2. Stepwise luminance changes resulted in transient blindness and decreased performance.

3. The spatial distribution of the lighting environment parameters significantly influences a driver's visual performance, and the effects are different in threshold, transition and interior zones.

4. The optimization of the spatial distribution of the lighting environment parameters should be considered in tunnel lighting design.