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Research article

The influence of dimming-induced luminance change on driving safety in tunnels

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ABSTRACT

Although dimming the light in tunnels brings salient benefits to energy saving, the effects of dimming-induced luminance changes on driving safety have been rarely explored. Adopting the visual performance experiment, the present study investigated the impacts of the dimming-induced luminance change rate (V) on the safety of driver's perception, judgment, and operation in the threshold zone of the tunnel under different seasons and weather conditions. The results show that the reaction times (RTs), pupil area change rate (v_p), and blink frequency (f_b), increased with the increase of V. When the luminance before the beginning of dimming (L) was higher, drivers reacted faster and stood a lower level of the mental load and fatigue. Compared with decreasing the luminance through dimming, when increasing the luminance through dimming, the present study found that each of the visual performance indices was about 10% lower, and the changes with V became smaller. Based on the safety thresholds of RT, v_p, and f_b, the present study obtained the thresholds of V which can meet the safety requirements of driver's perception, judgment, and operation. Finally, a theoretical model between the thresholds of V and L was developed, and this model will shed light on the control of V in the threshold zone of the tunnel under different seasons and weather conditions.

1. Introduction

The drastic changes in the light environment approaching the tunnel portal decrease the ability of the driver's visual recognition and thus cause traffic accidents [1]. To avoid this, installing lights in the threshold zone (the first part of the tunnel directly after the portal) has become an effective approach [2]. The threshold zone luminance (L_{th}) is determined by the average luminance of the surrounding near the portal in the 20° conical field of view (L_{20}), the traffic flow, and the vehicle speed [3]. According to the International Commission on Illumination (CIE), L_{th} should be designed based on three references, i.e., the highest L_{20} (likely to occur during at least 75 daytime hours per year), the maximum traffic flow, and the maximum vehicle speed [4]. However, the actual L_{20},

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traffic flow, and vehicle speed, are often much smaller than the above references [5,6,7,8]. Therefore, if the threshold zone luminance always adopts the designed value, it will lead to the fact that the lighting luminance is much higher than the real demand during the 95% of the daytime [9], thus resulting in over-illumination [10]. To eliminate over-illumination and reduce the consumption of lighting energy, dimming has been widely applied to the field of tunnel lighting [11,12].

In the field of tunnel lighting, dimming primarily includes step dimming and continuous dimming [11,13]. Compared with step dimming, continuous dimming has enjoyed higher prevalence owing to its more adjustable levels and continuous changes in luminance. For example, Qin et al. [14] designed a “vehicle in, light brightens; vehicle out, light darkens” continuous dimming system. In other words, when a vehicle is about to enter the tunnel, the system determines the lighting demand according to the real-time L_{20}, traffic flow, and vehicle speed, and then adjusts the lighting power to meet the real demand; when there are no vehicles in the tunnel, the luminaire operates at 10% of its rated power. This system has been applied to the Chibai tunnel on Tong Shen Expressway (China), and the results show that the energy consumption of tunnel lighting was reduced by 45%. However, the switching frequency of "light brightens" and "light darkens" is high (up to 23 times per hour) due to the frequent entries and exits of the vehicles during heavy traffic periods, reducing the lifespan of the dimming system. To strike balance between the energy-saving benefits and the lifespan of the dimming system, Qin [15] grouped the daily traffic flow distribution into six time periods using the K-MEANS clustering algorithm, based on the traffic flow data retrieved from five actual tunnels. During heavy traffic periods, Qin [15] performed dimming according to real-time L_{20}, traffic flow, and vehicle speed; during the light traffic periods, they used the strategy of “vehicle in, light brightens; vehicle out, light darkens”. The results show that this dimming method can reduce the switching frequency of "light brightens" and "light darkens" by 16%–47% when the daily traffic flow ranged from 750 to 2500 vehicles. Nonetheless, detailed descriptions concerning the control mechanisms and algorithmic processes of existing dimming systems are still lacking in previous studies. To fill this gap, Zhao et al. [16] described the lighting demand calculating model which was based on the fuzzy control algorithm, and designed the corresponding fuzzy controller as well as a dimming control system. This system can save 30% energy consumption. The lighting demand calculation model was further improved by Zhao [7] using the LSTM algorithm, which achieved continuous dimming and increased energy savings of the dimming system to around 40%. In addition, based on data retrieved from 11 tunnels, Qin [17] explored the influences of tunnel length, traffic flow, and service time on initial investment and electrical costs for four kinds of dimming systems. The results show that when the service time was long (i.e., ≥955 days), the intelligent dimming had the lowest sum

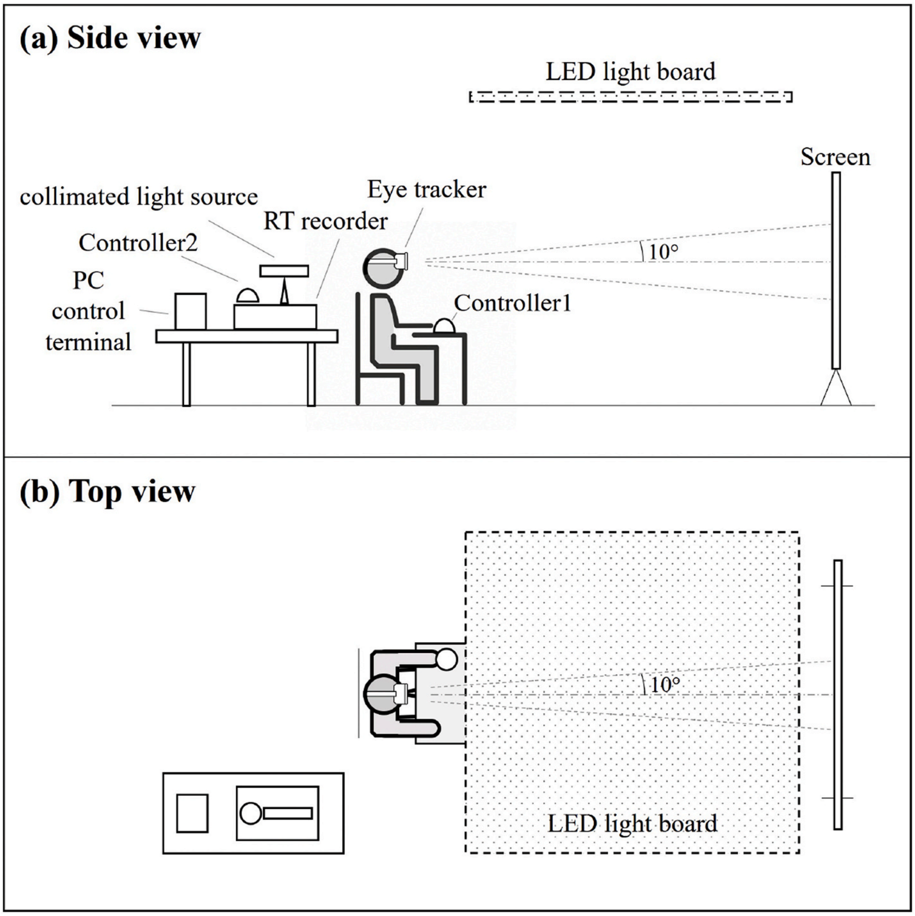

Fig. 1. The visual performance experiment platform.

of the initial investment and electrical costs and the best economic efficiency over the whole life cycle of the tunnel; when the service time was short (i.e., ≤218 days), "no-control low-consumption lamps" had the lowest sum of initial investment and electrical costs.

Previous studies and engineering practices have emphasized the energy-saving benefits of the tunnel dimming. However, an inevitable fact is that the luminance changes during dimming can cause safety problems. Zhao, Qin, and other researchers [14,16,17] pointed out that when a dimming was finished, the actual luminance and luminance uniformity may not meet the driver's perception demands, which resulted in difficulties of drivers seeing obstacles clearly on the road ahead. This problem can be solved by installing additional "luminance detection-feedback-adjustment" devices [8] and optimizing the lighting fixtures layout [18]. In addition, it should be noted that factors affecting the lighting demand of the threshold zone vary constantly during the day, and one of the affecting factors, L_{20}, varies particularly sharply. When analyzing the energy-saving of the dimming system based on measured L_{20}, Doulos [19,20] found that there were frequent "jumps" in L_{20} variations, i.e., a sudden increase or decrease; in some extreme cases, the varying magnitude of L_{20} within 5 min reached 2 kcd/m^2 or more, leading to drastic luminance changes in the threshold zone. These changes will lead to a sharp increase in the pupil change rate (called "visual oscillation"), resulting in a sharp reduction in the visual performance and comfort of the driver [21]. The indoor experiments conducted by Schreuder [22] showed that sudden changes in luminance temporarily prevented drivers from detecting small target obstacles (probability: above 25%). Through real vehicles and indoor experiments, previous studies [23,24,25] found that a rapid decrease in luminance by 50%–65% resulted in a 20% increase in driver's reaction times (RTs), a threefold increase in the missed target rates, and more frequent changes in gaze location and duration, which indicates a stressful state in both physiology and psychology of the driver. To sum up, instantaneous and drastic luminance changes significantly decrease the driver's visual performance. It should be noted that previous studies have primarily focused on the influences of instantaneous and drastic luminance changes on drivers. However, during the dimming, the luminance changes continuously at a certain rate. But, the impact of dimming-induced luminance change rate on driving safety has not been investigated yet.

Therefore, adopting visual performance experiments, the present study aims to (1) investigate the effects of dimming rate (i.e., dimming-induced luminance change rate) on RTs and the pupil change in the tunnel threshold zone under different seasons and weather conditions, and (2) develop a theoretical model between the initial luminance (i.e., the luminance before the beginning of dimming) and the dimming rate that satisfies safety requirements. The model will shed light on enhancing driving safety during the dimming process in tunnels.

2. Methodology

2.1. Experimental platform

The visual performance experiment platform was built in a darkroom (Fig. 1(a and b)). The platform contained a lighting and control system, an RT test system, and an ASL eye-tracking system.

The lighting and control system included a LED light board, a collimated light source, and a PC control terminal. The LED light board was located at the ceiling of the darkroom to simulate the tunnel luminaires. The collimated light source was used to generate light spots as targets, and its orientation can be flexibly adjusted to meet experiment requirements. The LED light board and the collimated light source have the same color temperature, and their power was steplessly adjustable. The PC control terminal was used to synchronously control the power change of the LED light board and collimated light source, so that the luminance of the screen and targets can reach the preset conditions of the experiment.

The RT test system included a screen, a chin rest, two controllers of a collimated light source, and an RT recorder. The surface of the screen was approximately uniformly diffuse, with a reflectivity of about 0.8. The chin rest was located at a certain distance in front of the screen to fix the subject's chin, so that the subject's eyes were at the same level as the center of the screen. As for the two controllers of a collimated light source, one was used for turning on and the other for turning off the collimated light source. The RT recorder recorded RTs (from appearance to the disappearance of the target) with an accuracy of 0.1 ms.

The ASL eye tracking system consisted of an ASL control unit and an H6 head-mounted eye tracker. The system can capture data such as the pupil position and pupil diameter, with a sampling frequency of 60 Hz.

2.2. Parameters

According to CIE, CR, and JTG [3,4,26], the luminance demand of threshold zone 1(the first half within the threshold zone), i.e., L_{th1} (cd/m^2) is calculated as equation (1):

$$L_{th1} = L_{20} \cdot k \quad (1)$$

where, L_{20} (cd/m^2) is the average luminance in a 20° (2 × 10°) conical field of view, by an observer located at the reference point and looking towards a centered point at a height equal to one-quarter of the height of the tunnel opening; k is the proportions coefficient, which depended on the traffic flow and the vehicle speed according to JTG [26].

Equation (1) shows L_{20} is proportional to L_{th1}. Since the change of L_{th1} determines the luminance change of dimming, the luminance change of dimming depends on the change of L_{20}. Moreover, the present study focuses on the dimming of highway-mountain tunnels. For highway-mountain tunnels in China, the 20° conical field of view generally contains plants and walls of certain proportions, the sky area is 0 [26], and the tunnels have different portal orientations. To satisfy these features, three tunnels with different portal orientations were selected to measure values of L_{20}, and therefore the present measurements can be considered as representative in terms of L_{20} variations of China highway-mountain tunnels. L_{20} variations of three tunnels are shown in Fig. 2.

It can be seen from Fig. 2 that there are several large abrupt variations in L_{20} in each tunnel from 7:00 to 17:00. For example, the L_{20} of tunnel A reached about 3 kcd/m^2 and 1 kcd/m^2 before and after 10:15, respectively, and the L_{20} varied 2 kcd/m^2 within 7 min; the maximum abrupt variations in L_{20} of the tunnels B and C occurred at around 13:40 and 15:55, respectively, and also varied 2 kcd/m^2 within 10 min.

The above L_{20} data were used to further calculate the dimming-induced luminance change rate, based on which, we set the luminance change rates of the indoor experiment. At the end of a dimming, the average luminance in a 20° conical field of view was recorded as $L1$ 20, and the corresponding luminance demand of threshold zone 1 as $L1$ th1, i.e., $L1$ 20×k. Before the next dimming was about to start, the average luminance in a 20° conical field of view was recorded as $L2$ 20, and the corresponding luminance demand of threshold zone 1 as $L2$ th1, i.e., $L2$ 20×k. When the dimming started, the dimming system would adjust the luminance of threshold zone 1 from $L1$ th1 to $L2$ th1. The corresponding luminance change during this time of dimming was thus $L2$ th1−$L1$ th1 which depended on the change in L_{20} between two times of dimming, i.e., $L2$ 20−$L1$ 20. In practical situations, the time interval between two times of dimming is usually 10 min [7]. During this interval, the maximum change amplitude of L_{20} reaches 2 kcd/m^2 according to the above L_{20} measurements. Taking $k = 0.025$ (design speed 80 km/h, design traffic flow 350veh/(h/ln) that is commonly used in the tunnel, we can get that the change of luminance demand of threshold zone 1 is 50 cd/m^2 using equation (1), and the corresponding luminance change through dimming is 50 cd/m^2. Based on a single dimming duration of 8 s–15 s, the dimming-induced luminance change rate, i.e., dimming rate V, was calculated as 3.3 cd/(m^2·s) ~6.25 cd/(m^2·s). Therefore, we selected 3, 4, 5, 6, 7 cd/(m^2·s) as V values.

Depending on the recommended values of L_{20} [26], we calculated L_{th1} under different seasons and weather conditions, respectively, and these values were used as the initial luminance (L), ranging from 20 to 80 cd/m^2 ($k = 0.025$). Thus, we selected 20, 40, 60, and 80 cd/m^2 as L values as test conditions. The test conditions are summarized in Table 1.

The distance between the subject and the screen was 1.5 m. According to the actual tunnel luminaires, the color temperature of the LED light board was set as 4500 K. We adopted an achromatic task, i.e., the color temperature of the collimated light source is consistent with that of the LED light board. The target was a circle with a diameter of 28 mm [4,27], and its contrast C was 0.3, which was slightly higher than the minimum perceived contrast of 0.28 [25]; C is calculated by equation (2). The eccentricity of the target ranged from 0° to 10°, including the central vision and the peripheral vision [27].

$$C = \frac{\Delta L}{L_b} = \frac{L_t - L_b}{L_b} \tag{2}$$

where L_b (cd/m^2) is the luminance of the screen; L_t (cd/m^2) is the luminance of the target.

2.3. Procedure

Ten subjects (5 males, 5 females; 23–28 years old) with normal color vision and corrected visual acuity volunteered to participate in the present study. All of them were in good physical condition, had three to five years of driving experience, and held a driver's license for two years or more. All participants voluntarily participated in the study and gave written informed consent in accordance with the Declaration of Helsinki. The current study was approved by the Institutional Review Board of Zhejiang University.

The test process is shown in Fig. 3. In the preparation stage, the examiner (1) illustrated the instructions and calibrated the eye-

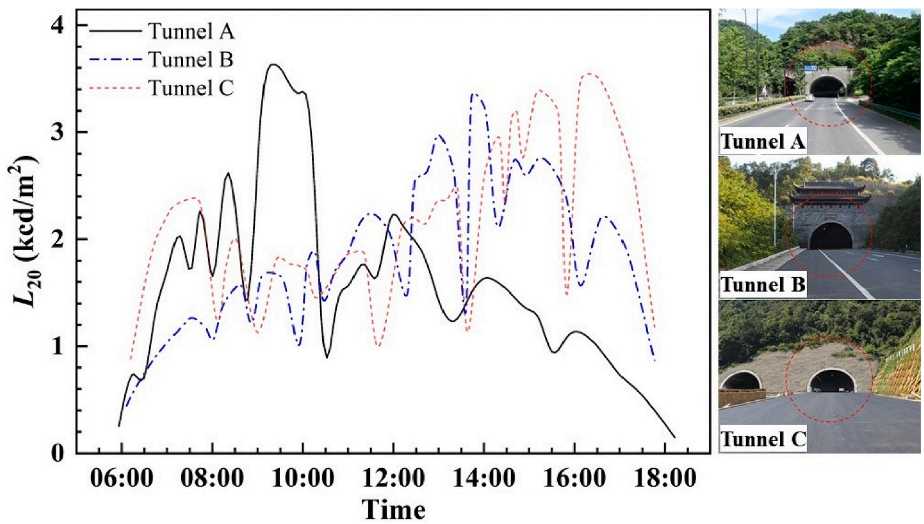

Fig. 2. L_{20} variations of three tunnels.

Table 1
Test conditions.

Variables	Conditions
Initial luminance L (cd/m^2)	20, 40, 60, 80
Dimming rate *V* ($cd/(m^2 \cdot s)$)	3, 4, 5, 6, 7

tracking instrument; then, (2) adjusted the power of the LED light board to make the screen reach the *L* and calibrated it with the luminance meter; and finally, (3) instructed the subject to adapt to the *L* for 3 min. In the test stage, luminance change lasted about 3s, which is consistent with the duration of driving in the threshold zone [26]. During this period, the examiner used controller 1 to make the target appear three times randomly. When the subject perceived the target, he/she needed to press controller 2 as quickly as possible and once the device detected the subject's responses, the target disappeared immediately. The eye-tracking device recorded the subject's eye movement simultaneously. After a test condition was completed (1 initial luminance × 1 dimming rate), the subject took a rest for 10 min [25].

2.4. Evaluation indices

90% of traffic accidents are related to drivers [28]. The driver's behavior can be summarized into three parts: perception, judgment, and operation [29] (Fig. 4). Firstly, the driver perceives information about the status of himself, the status of the vehicle, traffic conditions, the road, and the environment through vision and audition. Then, the driver makes judgments based on the above information to determine his next action. Finally, the driver needs to operate the vehicle. When the driver is operating the vehicle, new information is generated constantly, forming a continuous cycle of perception, judgment, and operation. Safety hazards at any part may disrupt the cycle and cause traffic accidents.

The probability of traffic accidents correlates negatively with the driver's perception speed [30], which is usually measured by RTs [31]. Therefore, the experiment used RTs as an evaluation index for the safety of the perception part.

30% of traffic accidents are caused by drivers' mistakes in judgment and operation, such as excessive speed and improper evasive actions, so the safety of judgment and operation should be highly emphasized as well [28]. One of the important reasons for mistakes in judgment and operation is the high level of mental load and fatigue of the driver at that time [32].

The mental load is defined as the workload of mental activity per unit of time and is positively correlated with the magnitude of the pupil area change [33]. Therefore, we used the change rate of pupil area (v_p), i.e., the magnitude of the pupil area changes per unit time, to characterize the magnitude of the mental load [21].

Driving tasks and the driving environment, especially the changes in the light environment at the threshold zone of the tunnel are more likely to cause task-related fatigue [34]. Therefore, the experiment focused on task-related fatigue and used the blink frequency for its quantitative evaluation [35,36].

The RT (ms) is calculated by equation (3):

$$\mathrm{RT} = \frac{\sum_{i=1}^{n} \mathrm{RT}_i}{n} \tag{3}$$

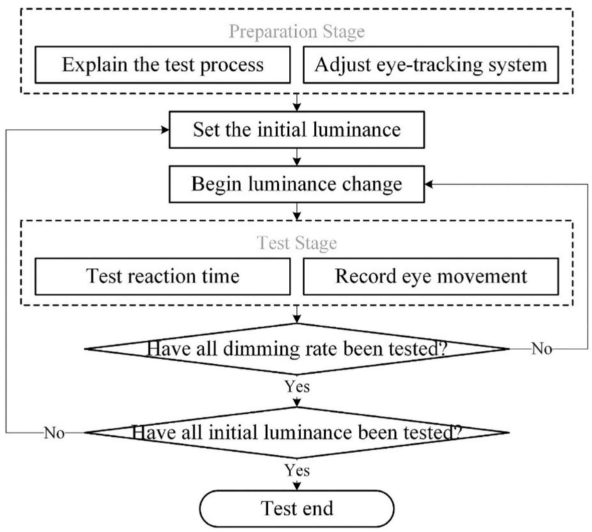

Fig. 3. Test procedure.

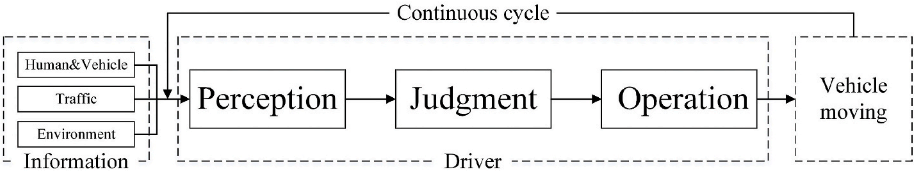

Fig. 4. Driver's behavior while driving.

where RT_i (ms) is the ith ($i = 1 \sim n$) reaction time obtained from the test under certain L and V; n is the times of collecting RT under a certain test.

The pupil area change rate v_p (mm^2/s) is calculated by equations (4) and (5):

$$v_{pi} = \left|\frac{dS}{dt}\right| \tag{4}$$

$$v_p = \frac{\sum_{i=1}^{n} v_{pi}}{n} \tag{5}$$

where v_{pi} (mm^2/s) is the instantaneous change rate of pupil area under a certain condition. The data of $S = 0$ mm^2, blink and the data near the blink, had been removed when we calculated v_{pi}; S (mm^2) is the pupil area; t is the duration of the test under certain L and V.

The blink frequency f_b (Hz) was calculated by equation (6):

$$f_b = \frac{N}{t} \tag{6}$$

where N is the total number of blinks of a subject under a certain condition.

3. Results and discussion

3.1. Decreasing luminance through dimming

To explore whether and how V and L affect RT, v_p, and f_b, several mixed effect models were established for RT, v_p, and f_b respectively when the dimming luminance decreased [37]. The fixed effects were V, L and the interaction effect between V and L, and the random effect was the random intercept of the subjects. The dependent variable was RT, v_p, and f_b, respectively. The main effects and interaction effects of each model are shown in Table 2.

As shown in Table 2, the main effects of V and L on RT, v_p, and f_b were all significant, $ps < 0.001$, indicating that V and L significantly influence RT, v_p, and f_b respectively; similarly, the interaction effects of V and L were all significant as well, $ps < 0.05$, indicating that the effects of V (or L) on RT, v_p, and f_b are significantly modulated by L (or V). Considering these significant interaction effects, further simple effect analyses were conducted and influences of V and L on RT, v_p, and f_b were discussed below.

Take the data under $L = 20$ cd/m^2 as an example. Changes of RT, v_p, and f_b with V during the luminance reduction through dimming are showed in Fig. 5(a–c). Fig. 5(a–c) shows that RT increased with the increase of V, indicating that subjects' perception slowed down. And Fig. 5(a–c) also demonstrated v_p, and f_b increased with the increase of V, and v_p and f_b were positively correlated with mental load and the degree of task-related fatigue, respectively [21,33,35,36], which suggests that levels of mental load and fatigue increased. It can be seen from Fig. 5 (a), RT showed a slow and then rapid growing trend as V increased. The results of simple effects analysis show that when V increased from 3 to 4 $cd/(m^2 \cdot s)$, changes of RT were not significantly different, $p = 0.960$; while when V increased from 5 to 7 $cd/(m^2 \cdot s)$, changes of RT were significantly different, $p < 0.001$. It thus can be seen from Fig. 5 (a) and results of simple effect analyses that when the dimming rate exceeds a certain range, drivers are affected by V, and their perception speed slows down significantly. As for the judgment and operation parts, the changes of v_p and f_b (Fig. 5(b) and (c)) were different from those of RT. Values of v_p at different values of V were significantly different, $ps < 0.001$, i.e., for every 1 $cd/(m^2 \cdot s)$ increase in V, v_p increased about 7%. f_b was in a normal range (0.25 Hz–0.5 Hz) [38] when V was 5 $cd/(m^2 \cdot s)$ or below. This is because the driving time in the threshold zone was only about 3 s. Within this short time, the relatively low luminance change rate did not cause fatigue. But when V was 6 $cd/(m^2 \cdot s)$ or above, despite the short time, the relatively drastic luminance changes still lead to dry eyes and frequent eye rotations.

Table 2
Results of $V \times L$ on RT, v_p, and f_b under the condition of decreasing luminance through dimming.

	Main effects of V	Main effects of L	Interaction effects
RT	$p < 0.001$	$p < 0.001$	$p = 0.002$
v_p	$p < 0.001$	$p < 0.001$	$p = 0.030$
f_b	$p < 0.001$	$p < 0.001$	$p < 0.001$

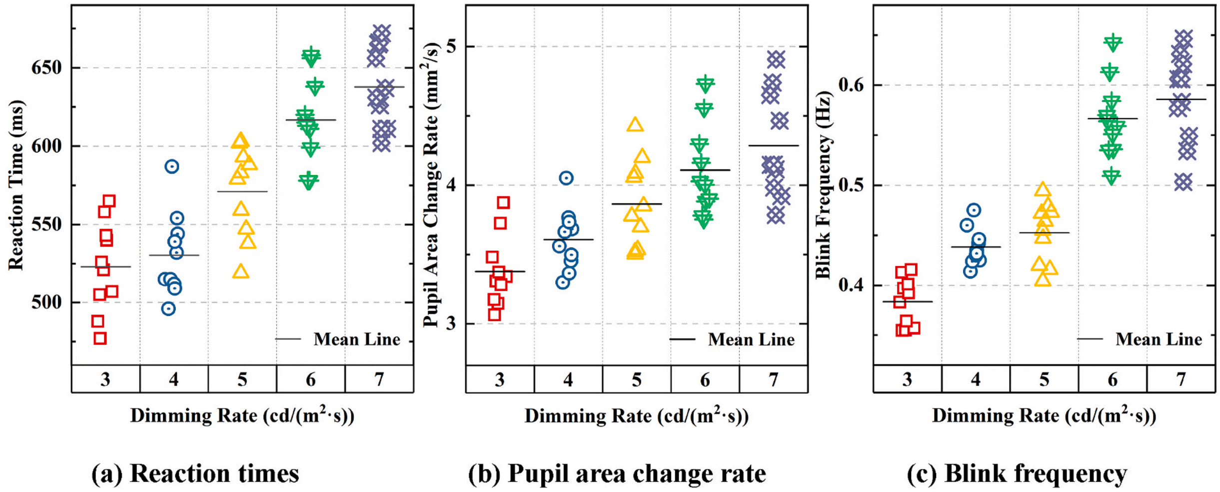

Fig. 5. The impact of dimming rate on visual performance when the luminance decreases through dimming. Note: A single data point represents the test data of a subject.

Thus, f_b exceeded the normal range (reached about 0.6 Hz).

Fig. 6(a–c) shows the changes of RT, v_p, and f_b with L at different V when decreasing the luminance through dimming. It can be seen that as L increased, RT, v_p, and f_b decreased rapidly first and then leveled off; and the larger the V is, the greater the variations of RT, v_p, and f_b with L. At high levels of L, due to low difficulties in perceiving targets [39,40] and small ratios of the luminance change to L (e.g., under the $V = 3$ cd/(m^2·s), when $L = 80$ cd/m^2 and $L = 20$ cd/m^2, the ratio is 0.04 and 0.15, respectively), subjects had a better visual performance: RT and v_p at $L = 80$ cd/m^2 are about 16% lower than those at $L = 20$ cd/m^2 ($V = 7$ cd/(m^2·s)), and f_b at $L \geq 60$ cd/m^2 is in the normal range, the highest being only 0.45 Hz. These results indicate that compared with the low initial luminance, dimming luminance change has a relatively less influence on the driver under the high initial luminance.

3.2. *Increasing luminance through dimming*

Similar to the statistical analyses in *Section 3.1*, three mixed effect models for RT, v_p, and f_b were established respectively when the dimming luminance increased. The main effects and interaction effects of the model are shown in Table 3.

As shown in Table 3, the main effects of V and L on RT, v_p, and f_b were all significant, $ps < 0.001$, indicating that V and L influence RT, v_p, and f_b respectively; the interaction effects of V and L were all significant as well, $ps < 0.05$, indicating that the effects of V (or L) on RT, v_p, and f_b are significantly modulated by L (or V). Due to the significant interaction effects, further simple effects analyses were conducted and influences of V and L on RT, v_p, and f_b were discussed as follows.

Take the data under $L = 20$ cd/m^2 as an example. Fig. 7(a–c) shows the changes of RT, v_p, and f_b with V when the luminance increases. RT, v_p, and f_b all increased with the increase of V, which is consistent with the pattern when the luminance decreased (Fig. 5

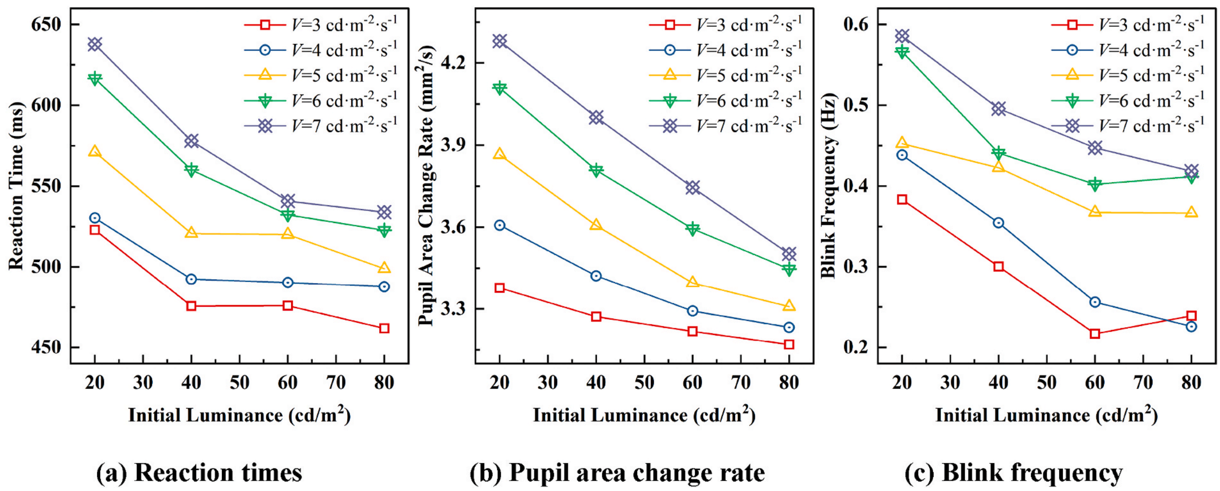

Fig. 6. The impact of initial luminance on visual performance when the luminance decreases through dimming.

Table 3
Results of $V \times L$ on RT, v_p, and f_b under the condition of increasing luminance through dimming.

	Main effects of V	Main effects of L	Interaction effects
RT	$p < 0.001$	$p < 0.001$	$p = 0.043$
v_p	$p < 0.001$	$p < 0.001$	$p = 0.039$
f_b	$p < 0.001$	$p < 0.001$	$p < 0.001$

(a–c)). While, differently, compared to the decrease of luminance (Fig. 5(a–c)), when the luminance increased, RT, v_p, and f_b were about 10% lower, the ranges of changes of these indices were about 50% smaller when V changed from 3 cd/(m^2·s) to 7 cd/(m^2·s), indicating that the deterioration of visual performance by luminance changes was weaker when the dimming luminance increased, and this is probably due to the better light adaptation ability of human eyes [4].

Fig. 8(a–c) shows the changes of RT, v_p, and f_b with L at different V when luminance increases through dimming. When L ranged from 20 cd/m^2 to 80 cd/m^2, RT, v_p, and f_b decreased with the increase of L, showing that the visual performance of the subject gradually increased. The results of simple effect analyses show that when luminance increased, RT, v_p, or f_b under most V was significantly different only when L was less than 60 cd/m^2, $ps < 0.001$. In contrast, when luminance decreased, RT, v_p, or f_b were different at most V under each L. This indicates that subjects are less sensitive to the changes in the dimming rate when the luminance increases through dimming.

3.3. Thresholds of the dimming rate

According to previous studies, RT = 570 ms [30], v_p = 4 mm^2/s and 6 mm^2/s (under luminance reduced and increased conditions, respectively) [41], and f_b = 0.25–0.5 Hz [38], were used as safety thresholds for perception speed, mental load, and fatigue level, respectively.

Based on the above safety thresholds, we processed the data of RT, v_p, and f_b. Take RT as an example. The 85% quantile of data for all subjects under a certain L and V were adopted and marked as RT_{85} [21]. Then, the V that makes RT_{85} reach the above safety thresholds under each L was obtained through the linear interpolation, and marked as the dimming rate threshold ($V_{thr\text{-}RT}$); if none of the RT_{85} reached the safety threshold under a certain L, the maximum value (7 cd/(m^2·s)) in the experiment was taken as the $V_{thr\text{-}RT}$. Correspondingly, we got v_{p85}, f_{b85}, and then $V_{thr\text{-}vp}$, $V_{thr\text{-}fb}$, respectively.

The $V_{thr\text{-}RT}$, $V_{thr\text{-}vp}$, $V_{thr\text{-}fb}$ obtained using the above process at each L are shown in Fig. 9.

As can be seen from Fig. 9., the $V_{thr\text{-}RT}$, $V_{thr\text{-}vp}$, $V_{thr\text{-}fb}$ all increased exponentially with the initial luminance. When the luminance decreased through dimming, $V_{thr\text{-}fb}$ was the largest, being all above 5.2 cd/(m^2•s) at any L; while $V_{thr\text{-}RT}$ and $V_{thr\text{-}vp}$ were relatively small, ranging from 4.3 cd/(m^2•s) to 6 cd/(m^2•s). It can be indicated that as long as RT, v_p (influenced by V in the present study) do not exceed their safety thresholds in the dimming process, the probability of drivers' errors in perception, judgment and operation is relatively low, so security risks of driving are relatively low.

While when the dimming luminance increased, most of the thresholds of the dimming rate under L were higher than 10% due to the relatively small impact of RT, v_p, and f_b by V. Especially for the pupil area change rate, v_{p85} did not exceed the safety threshold within the L and V ranges in the experiment, indicating that the dimming luminance changes did not make the subject's mental load too high to influence the driving safety. Meanwhile, the threshold of the dimming rate based on the RT safety threshold was the smallest, indicating that among the driver's perception, judgment and operation, the perception part is the key to driving safety.

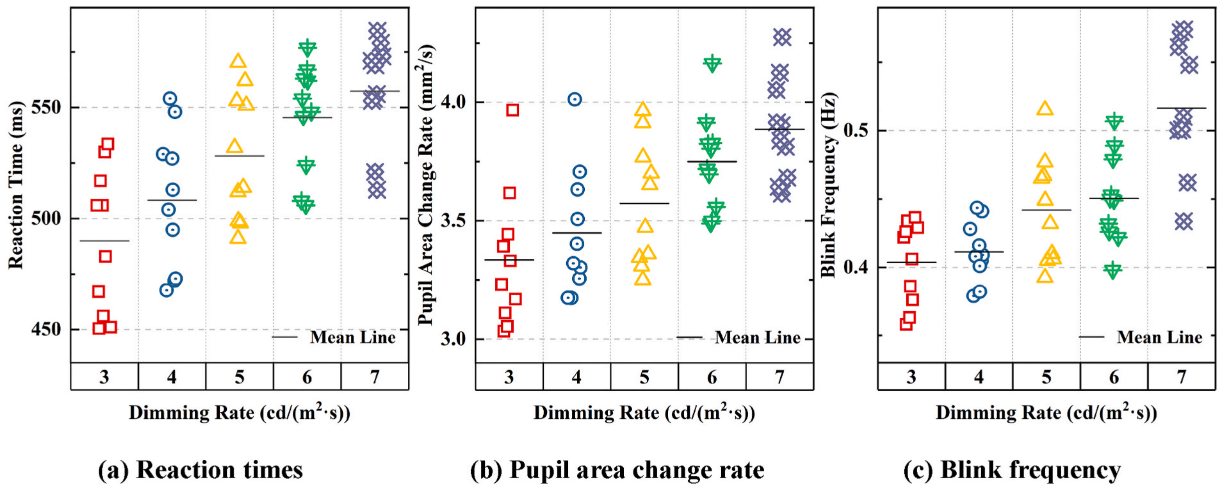

Fig. 7. The impact of dimming rate on visual performance when the luminance increases through dimming. Note: A single data point in the figure represents the test data of a subject.

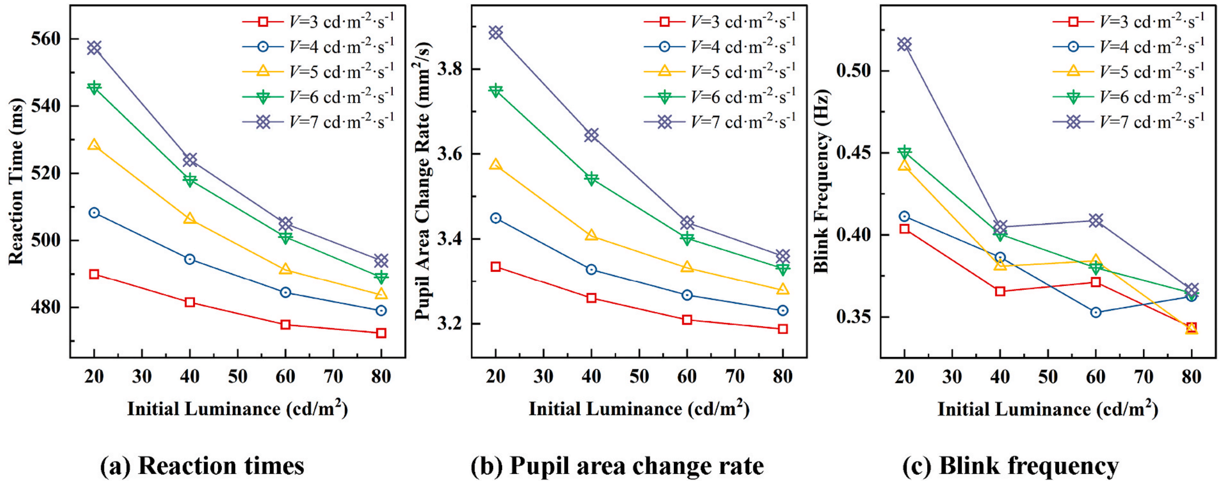

Fig. 8. The impact of initial luminance on visual performance when the luminance increases through dimming.

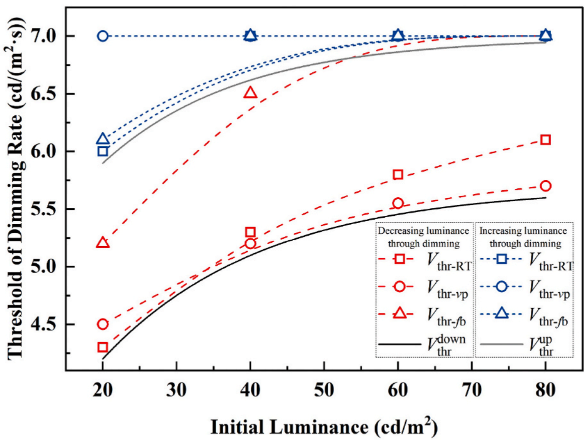

Fig. 9. The changes of dimming rate thresholds with the initial luminance.

Furthermore, an exponential function is used to fit the L versus threshold of the dimming rate that satisfies the safety thresholds of RT, v_p, and f_b:

$$V_{thr}^{down} = 5.69 - 3.74 \cdot (0.96)^L \quad (R^2 = 0.998, p = 0.006) \tag{7}$$

$$V_{thr}^{up} = 6.98 - 3.23 \cdot (0.95)^L \quad (R^2 = 0.989, p = 0.049) \tag{8}$$

where *V*down thr (cd/(m^2·s)) is the thresholds of dimming rate under the condition of luminance decrease; *V*up thr (cd/(m^2·s)) is the thresholds of dimming rate under the condition of luminance increase.

According to equations (7) and (8), the dimming rate should be set following the initial luminance to meet the drivers' safety demands during the dimming in the threshold zone. Particularly, under the condition of low initial luminance, such as on cloudy days in winter and autumn, the dimming rate should be strictly limited.

Compared with previous studies, when the luminance changes from 26.25 cd/m^2 to 8.75 cd/m^2 in an instant (within approximately 1 s) [25], the corresponding luminance change rate is about 17.5 cd/(m^2·s). Affected by the changes of luminance, the reaction time of the subjects reached 827 ms, i.e., about 45% higher than the safety threshold of 570 ms, indicating that the instantaneous high luminance change rate can significantly increase the traffic safety risk. The test condition at the initial luminance of 20 cd/m^2 in the present study is close to that in He et al. [25]. In this test condition, under the common dimming rate in the tunnel (3–7 cd/(m^2·s)), the reaction time of the subjects was 520–640 ms, which still exceeds the safety threshold. When we use the model proposed by the current research, the dimming rate is controlled below 4.3 cd/(m^2·s) for the initial luminance of 26.25 cd/m^2. At this time, the subjects' reaction time is less than 570 ms, which is lower than the safety threshold. Therefore, it can be concluded that the present model succeeds in reducing the risk of traffic safety during dimming in tunnels effectively.

4. Conclusion

The present study revealed four major findings. First, with the increase of the dimming rate (V), all indices of visual performance increased, the subject's perception speed slowed down, and the mental load and level of fatigue increased. The reaction times (RTs) showed an increasing trend ranging from a slow to rapid speed; pupil area change rate (v_p) increased approximately linearly; blink frequency (f_b) was beyond the normal range at $V \geq 6$ cd/(m^2·s). When V was held constant, the higher the initial luminance (L), the faster the subject's perception speed, and the lower the driver's mental load and level of fatigue, which indicates that subjects are less affected by the luminance change through dimming.

Second, compared to decreasing luminance through dimming, when luminance increased through dimming, RT, v_p, and f_b were about 10% lower, and their change ranges with V were smaller, which is due to the better light adaptation capacity of human eyes. The effect of the luminance decrease through dimming on the visual performance is more salient than that of the luminance increase.

Third, all the thresholds of the dimming rate that meet the safety thresholds of RT, v_p, and f_b, respectively, increase exponentially with the increase of L. The thresholds of the dimming rate that meet the safety threshold of RT were the lowest, being only 4.3 cd/(m^2·s) and 6 cd/(m^2·s) when the luminance decreased and increased, respectively, indicating that among the driver's perception, judgment and operation, the perception part is the key to the driving safety during the dimming.

Fourth, the present study developed a theoretical model, i.e., equations (7) and (8), between the initial luminance and the thresholds of the dimming rate (i.e., *V*down thr, luminance decrease, and *V*up thr, luminance increase). Moreover, *V*down thr and *V*up thr can meet the safety demands of driver's perception, judgment, and operation. The present study proposed that the upper limit of the dimming rate should be well controlled under different initial luminance conditions, such as different seasons and weather, to enhance the safety of driving in the dimming process in tunnels.

To conclude, adopting the visual performance experiment, the present study explored influences of the dimming-induced luminance change rate on the safety of driver's perception, judgment, and operation in the threshold zone of the tunnel under different seasons and weather conditions, and proposed a theoretical model between the initial luminance and the thresholds of the dimming rate. Future studies may conduct real vehicle experiments to further explore the influences of dimming-induced luminance change in real tunnels, and further refine the current model.

Author contribution statement

Chi Zhang: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Cheng Kang: Conceived and designed the experiments; Performed the experiments.

Lei Ye; Jiajun Weng; Zhiyi Huang: Contributed reagents, materials, analysis tools or data.

Ke Wu: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Data availability statement

Data will be made available on request.

Declaration of interest's statement

The authors declare no conflict of interest.

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