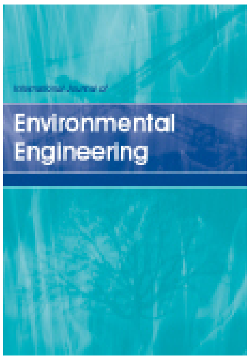

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Theoretical and experimental analysis of the passenger's reading comfort to luminous environment in Chinese high-speed trains

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Abstract: This paper is aimed at finding the nature of passengers' reading comfort in Chinese high-speed trains to the luminous environment. First, based on the ideology of photon mapping, the theoretical analysis is conducted to reveal the mechanism of the passengers' reading comfort qualitatively. Then, based on the experimental data gained from the comprehensive comfort test-rig, the mechanism of the reading comfort is developed quantitatively based on fuzzy algorithm. Results show that the best illumination for the reading passengers ranges from 175 Lux to 450 Lux and the best range of the colour temperature should be approximately natural. Moreover, the higher the illumination is, the more likely that the passengers will feel comfortable in higher degree of colour temperature. These conclusions can be applied in guiding the design of the comfortable luminous environment of Chinese high-speed trains.

Keywords: luminous environment; illumination; colour temperature; reading comfort; Chinese high-speed trains.

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1 Introduction

The high-speed trains have become universal ways of public transportation in China. Simultaneously, the increasing living standard of Chinese citizens makes it urgent to optimising the riding experience. Luminous environment a factor affecting the passengers' riding comfort. Thus, the research of luminous environment inside Chinese high-speed trains is of great importance.

Researches relating to the luminous environment in Chinese high-speed trains have been reported by many researchers. Su et al. (2013a) developed illumination comfort model of high-speed trains by linear fitting, in which the absolute value and change rate are taken into consideration. Moreover, based on their former researches, Su et al. (2013b) built the evaluation algorithm of luminous comfort under different illuminations and illumination change rates. However, Su's research did not consider the effect of colour temperature. Zhang and Xu (2012) summarised the effect of colour temperature, illumination, lighting method and distribution on the passengers' riding comfort, but the mechanism and evaluation method have not reported.

However, with the enhancement of Chinese educational level, there are more and more passengers choosing reading on the train as a recreation of their travel. But, there is nearly no literature reported on the comfort of luminous environment for reading passengers in Chinese high-speed trains.

Howerver, in some other related fields, the relationship between lighting conditions and the reading comfort has been studied. Shen et al. (2009) studied the lighting and font style on visual performances and fatigue with the electronic paper display via experiments. Avcı and Memikoğlu (2017) investigated the effects of the LED lights on visual comfort and concluded that the illumination of 500 Lux is favourable for Turkey. Lege et al. (2017) surveyed the best illumination range of the visibility of the electronic devices and concluded that the optimum illumination of reading should be higher than 200 Lux and the illumination of 300 Lux to 500 Lux is much more excellent for Japanese. Nevertheless, all these researches of reading comfort of luminous environment in other fields or other countries may not meet the situation of the Chinese high-speed train, as a result of physical or environmental differences.

Moreover, most of these studies did not consider the theoretical mechanism in their analysis. Thus, there is the need to research the effect of luminous environment on the reading passengers' comfort of Chinese high-speed trains theoretically. Studies show that various objective factors can be applied in reflecting the visual comfort of the human's. Apart from the illumination directly, Dobres et al. (2017), Marlow et al. (2017) and some other scholars chose the resolution contrast to the printed words as an indicator of comfort, while the retinal illumination was selected by Thibos et al. (2018). Moreover, Choi et al. (2018) chose the pupil size as an indicator of visual comfort. However, all the indicators do not indicate the degree of visual comfort directly, but show the trend of comfort alteration. Thus, they can be chosen as the qualitative indicators of visual comfort in Chinese high-speed trains. But unfortunately, the reading comfort of human is an entirely subjective issue that makes it difficult to evaluate the passengers' comfort quantitively via entirely theoretical approach. Thus, the experimental analysis is also needed.

Therefore, based on the real needs of the train passengers and current situations of luminous comfort research, a new mechanism should be developed by qualitatively theoretical and quantitatively experimental analysis. And some further issues concerning the optimum range, the comparison with some other researches in other fields and the suggestions will be disscussed based on the analysis results.

2 Theoretical analysis

The theoretical analysis is aimed at finding the nature of the luminous comfort and the qualitative trend of the luminous comfort alteration. The steps of theoretical analysis are,

1. Calculate the luminance and colour temperature of the objective colour (the colour printed on the material) and the ambient environment.
2. Find some criteria to predict the luminous comfort or the trend of comfort alteration.
3. Conclude the qualitative law of the alteration of the comfort.

Owing that the specular reflection and the penetration are much weaker than diffuse reflection, so only the diffuse reflection is taken into account in this research.

Some constant are taken in this section, namely,

- Planck's constant: $h = 6.626 \times 10^{-34}$ J·s
- Velocity of the light in vacuum: $c_l = 3 \times 10^8$ m/s.
- Absolute spectral luminous efficiency: $K_m = 683$ lm/W.
- Minimun detectable angle of human eyes: $\varphi_a = 1''$.

2.1 Calculation of luminance and colour temperature

The diffuse lighting parameters can be calculated based on the ideology of the photon mapping (Jensen, 1996; Pattamaik and Mudur, 1992) and computer illumination generation (Phong, 1975).

According to the fundamental laws of the photometry (Yu, 2006; Jin, 2006), the illumination can be calculated as follows,

$$I_i = \frac{d\Phi_i}{dA_i} \tag{1}$$

where Φ_i is the input luminous flux, and A_i is the area of the input lights penetrating. And it should be noted that the flux of Φ_i is not the same as the radiant flux of the light, CIE suggested that the luminous flux can be calculated by the following equation (He et al., 1979),

$$\Phi_i = \int_{380}^{780} K_m V(\lambda)\Phi_r(\lambda)d\lambda \tag{2}$$

alternatively, written as its discretised form,

$$\Phi_i = K_m \sum [V(\lambda_c)\Phi_r(\lambda_c)] \tag{3}$$

where $\Phi_r(\lambda_c)$ is the radiation flux of the light with the wavelength of λ_c, and $V(\lambda_c)$ is the relative spectral luminous efficiency function recommended by CIE. In general, the vision in the vehicles is photopic. Thus, the value of $V(\lambda_c)$'s are 0.0178, 0.9838, 0.0041 for the blue lights (435.8 nm), the green lights (546.1 nm) and the red lights (700.0 nm), respectively (Sharpe et al., 2005; Akasaki et al., 1992).

Moreover, based on the Planck's Formula, the radiation flux can be calculated by the following equation,

$$\Phi_r(\lambda_c) = \alpha_c \frac{hc_l}{\lambda_c} \tag{4}$$

The light colour can be expressed as the RGB form, namely,

$$\mathbf{c} = [r, g, b]^T \tag{5}$$

where r, g, b ranges from 0 to 255, and the proportion of them indicates the proportion of the luminance. The luminous flux can be expressed as,

$$\Phi_i = K_m hc_l \left(\frac{\alpha_r V_r}{\lambda_r} + \frac{\alpha_g V_g}{\lambda_g} + \frac{\alpha_b V_b}{\lambda_b} \right) \tag{6}$$

where $\alpha_r : \alpha_g : \alpha_b = \frac{r\lambda_r}{V_r} : \frac{g\lambda_g}{V_g} : \frac{b\lambda_b}{V_b}$, and α_r, α_g or α_b are the number of the input red, green or blue phontons. Then, if the r, g, b value is known, then the luminous flux can be estimated by determining the number of coloured phontons (expressed as α_c, where c = r, g, or b).

Another factor concerning the input light is colour temperature. The steps of the colour temperature – RGB convention are, 1 Tranfer the colour temperature into the x, y, z value of CIE-XYZ. The relationship between the colour temperature and x, y, z defined in CIE-XYZ (McCamy, 1992) is,

$$\begin{cases} z = 1 - x - y \\ m = \frac{x-0.3320}{0.1858-y} \\ T = 449n^3 + 3{,}525n^2 + 6{,}823.3n + 5{,}520.33 \end{cases} \tag{7}$$

with $x \in [0,1]$, $y \in [0,1]$ and $z \in [0,1]$; and where T is the colour temperature.

From equation (7), it can be deduced that

$$y \leq 1 - x \tag{8}$$

Then, the convention from the colour temperature to the x, y, z defined in CIE-XYZ can be conducted if find x, y, z that suits the equations (7) and (8).

2 From the x, y, z value of CIE-XYZ, calculate the r, g, b value of CIE-RGB (Fisenko and Lemberg, 2016) by equation (9).

$$\begin{bmatrix} r' \\ g' \\ b' \end{bmatrix} = \frac{1}{y} \begin{bmatrix} 3.24045 & -1.53714 & -0.49853 \\ -0.96927 & 1.87601 & 0.04156 \\ 0.05564 & -0.20403 & 1.05722 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix} \tag{9}$$

3 Convert the CIE-RGB into RGB value.

$$c = \begin{cases} \frac{12.92c'}{\max\{r',g',b'\}} & c \leq c_0 \\ \sqrt[11]{(\frac{255c'}{\max\{r',g',b'\}} + 1.055)^5} - 0.055 & c > c_0 \end{cases} \tag{10}$$

where c_0 = 0.003131.

Because that the blue LED diodes can not offer adaquate illumination in the past, so the widely-used range of colour temperature of 2,500 K to 6,500 K is selected in the theoritical analysis (Akasaki et al., 1992). Figure 1 shows the r, g, b value of the corresponding colour temperature.

To simplify the calculation of RGB, a polynomial curve fitting is conducted in the range of 2,500 K to 6,500 K. To achieve a reasonable precision and maximum simplification, the order of the polynomial curve is selected as 2 and expressed in the form of matrix. Then, the mapping function between the colour temperature ranges from 2,500 K to 6,500 K can be established, namely

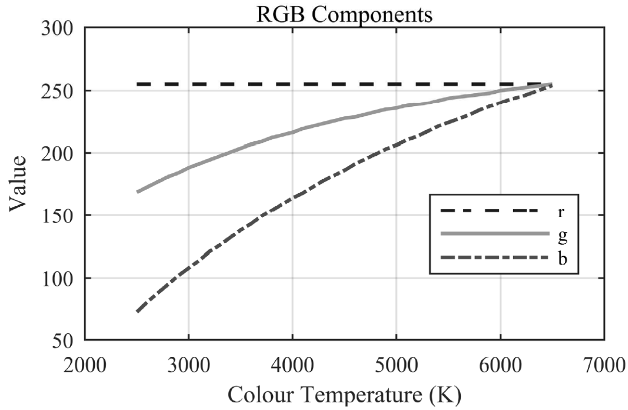
$$\mathbf{c} = \mathbf{HT} \tag{11}$$

where $\mathbf{c} = [r, g, b]^T$, $\mathbf{T} = [T^2, T, 1]^T$ and $\mathbf{H}$ is the transform matrix, and can be expressed as,

$$\mathbf{H} = \begin{bmatrix} 0 & 0 & 255 \\ -3.635 \times 10^{-6} & 0.05285 & 64.57 \\ -5.675 \times 10^{-6} & 0.09514 & -126.7 \end{bmatrix} \tag{12}$$

Then the interaction between the photons and material should be studied. Assuming that the number of the interaction between the photons and reading material is no more than once and the photons can be either absorbed or reflected, no photons can penetrate the reading material, the interaction of the photons can be studied.

Figure 1 The RGB value of corresponding colour temperature



2.1.1 Absorption

Supposing the colour matrix of the reading material is,

$$\boldsymbol{C_M} = [R_M, G_M, B_M]^T \tag{13}$$

where R_M, G_M, B_M are the red, green, blue components of the material, ranges from 0 to 255.

According to the law of the light absorption, the probability matrix of absorption of a specific coloured photon is,

$$\boldsymbol{P_a} = (255 - \boldsymbol{C_M})/255 \tag{14}$$

where $\boldsymbol{P_a} = [P_R, P_G, P_B]^\mathrm{T}$, and P_R, P_G, P_B are the probability of absorption of red, green, blue photons, respectively.

2.1.2 Reflection

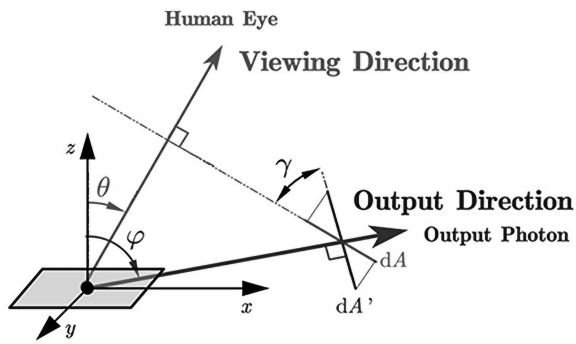
According to the fundamental law of diffuse reflection, the probability density of the output direction is uniform on the incident side of the reading material and zero on another side. The matrix of number of reflected photons follows,

$$\boldsymbol{B_C} = \frac{\boldsymbol{a_c C_m}}{255} \tag{15}$$

where $\boldsymbol{B_C} = \begin{bmatrix} \beta_R \\ \beta_G \\ \beta_B \end{bmatrix}$, and $\boldsymbol{a_c} = \begin{bmatrix} \alpha_r & 0 & 0 \\ 0 & \alpha_g & 0 \\ 0 & 0 & \alpha_b \end{bmatrix}$. Moreover, β_R, β_G and β_B are the number of output red, green and blue photons.

Then the output luminance and colour temperature can be calculated. All the needed parameters of output luminance calculation are shown in Figure 2.

Figure 2 The schematic diagram of the output luminance calculation



Similar as equation (1) shows, in the surface perpendicular to the viewing direction,

$$\frac{d\Phi_{oT}}{dA} = \sum_{i=1}^{n}\sum_{j=1}^{m}\frac{d\Phi_o(\lambda_i)}{dA'(\gamma_j)} \tag{16}$$

where Φ_{oT} is the total output luminous flux, and A is the area of the output lights penetrating.

From Figure 2, the infinitesimal of the area in the output direction is,

$$dA' = \frac{dA}{\cos\gamma_j} \tag{17}$$

Meanwhile,

$$\cos\gamma_j = \cos(\varphi_j - \theta) = \cos\varphi_j\cos\theta + \sin\varphi_j\sin\theta \tag{18}$$

then the equations (16) to (18) can be rewritten as,

$$\frac{d\Phi_{oT}}{dA} = \sum_{i=1}^{n}\sum_{\forall\varphi_j\in\Gamma}\frac{d\Phi_{oT}(\cos\varphi_j\cos\theta + \sin\varphi_j\sin\theta)}{dA} \tag{19}$$

where Γ is the set of output angle (φ_j), namely,

$$\Gamma = \{\varphi | -90\,\text{deg} < \varphi < 90\,\text{deg}\} \tag{20}$$

Meanwhile, the luminous flux of the output photon is,

$$\Phi_o(\lambda_n) = K_m V(\lambda_n)\frac{hc_l}{\lambda_n}\Theta_C \tag{21}$$

where

$$\Theta_C = \sum_{j=1}\beta_C(\cos\varphi_{cj}\cos\theta + \sin\varphi_{cj}\sin\theta) \tag{22}$$

Considering that the α_N is relatively high, the equation (22) can be rewritten as,

$$\Theta_C \approx \beta_C \left(\cos\theta \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \cos\varphi d\varphi + \sin\theta \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \sin\varphi d\varphi \right) = 2\beta_C \cos\theta \tag{23}$$

where $\theta \in [-\frac{\pi}{2}, \frac{\pi}{2}]$.

If dA is approximately zero, the solid angle of the light beams is $\Omega = 2\pi$. Then, the total output diffuse luminance is,

$$L_o = \frac{K_m h c_l \cos\theta}{\pi dA} \left[\frac{\beta_R V(\lambda_R)}{\lambda_R} + \frac{\beta_G V(\lambda_G)}{\lambda_G} + \frac{\beta_B V(\lambda_B)}{\lambda_B} \right] \tag{24}$$

The output RGB value matrix can be calculated by the number of the coloured photons and its direction, namely,

$$\boldsymbol{C'} = \begin{bmatrix} R' \\ G' \\ B' \end{bmatrix} = \frac{\boldsymbol{Q'}}{\sum_{q_c \in \boldsymbol{Q'}} q'_c} \tag{25}$$

where

$$\begin{cases} \boldsymbol{Q'} = [q'_R, q'_G, q'_B]^{\mathrm{T}} \\ q'_c = \frac{V_c \sum_{i=1}^{\beta_C} \cos\gamma_{Ci}}{\lambda_c} \end{cases} \tag{26}$$

considering that β_C is relatively high, and γ_{Ci} is uniformly distributed (Jin, 2006), then,

$$\boldsymbol{C'} \rightarrow \frac{\boldsymbol{Q}}{\sum_{q_c \in \boldsymbol{Q}} q_c} \tag{27}$$

where

$$\begin{cases} \boldsymbol{Q} = [q_R, q_G, q_B]^{\mathrm{T}} \\ q_c = \frac{V_c \beta_C}{\lambda_c} \end{cases} \tag{28}$$

And $\boldsymbol{C}$ is the matrix of RGB value (ranges from 0 to 255) of the output, namely,

$$\boldsymbol{C} = \begin{bmatrix} R \\ G \\ B \end{bmatrix} = \frac{255\boldsymbol{C'}}{\max\{\boldsymbol{C'}\}} \tag{29}$$

2.2 Evaluating criteria

2.2.1 Angular visual acuity

It has been a long time since the visual acuity was put forward by Shalaer (1937). Moreover, according to the research of Bailey et al. (1993), to achieve a more accurate vision of the detail, the minimum visual angle should be the quadruple of the detectable angle. Then, the angular visual acuity (AVA) can be defined by the minimum value of angle ensuring the accurate vision of detail and can be calculated by the interpolated function,

$$AVA = 4\varphi_a = \begin{cases} \frac{4}{10^{-0.1176p^2-0.009327p-0.8868}} & p \le -1 \\ \frac{4}{10^{0.007243p^3-0.1003p^2+0.4711p-0.3633}} & p > -1 \end{cases} \tag{30}$$

where $p = \log L$, φ_a is the minimum detectable angle of human vision and its unit is second ($''$), for normal eyes, the minimum φ_a is around $1'$. Thus, the maximum value of AVA that ensures the accurate vision is around 4. Moreover, a lower AVA means a higher visual acuity.

The luminance, L, are taken as the average ambient luminance (L_a), which is taken as the luminance reflected by the white paper, the L_a can be calculated via,

$$L_a = \frac{I_i \cos\theta}{\pi} \tag{31}$$

2.2.2 Relative visual acuity

The relative visual acuity (RVA) is defined as the quotient of the reciprocal of the φ_a under any illuminations and viewing angles and the maximum value of the reciprocal of the φ_a under the viewing angle of 0 deg, that is,

$$RVA = \frac{\frac{1}{\varphi_a}}{\max\{\frac{1}{\varphi_a}\}} \tag{32}$$

2.2.3 Relative retinal illuminance

The size of the human pupil can be altered with the variation of the surrounding luminous environment. Thus, the area of the light beam passing into the eyes can be changed. The diameter of the pupil is in negatively and nonlinearly correlation of the ambient luminance, usually (Watson and Yellott, 2012),

$$D_p = 4.9 - 3arctan[0.4lg(L_a)] \tag{33}$$

where D_p is the diameter of the human pupil (mm).

Moreover, the retinal illuminance is the production of the luminance (cd/m^2) and the area of the pupil (mm^2) (Thibos et al., 2018; Stiles, 1982), that is,

$$\epsilon = LS_p = \frac{L\pi D_p^2}{4} \tag{34}$$

moreover, the relative retinal illuminance (RRI) is

$$RRI = \frac{\epsilon}{\max\{\epsilon\}|_{\theta=0}} \tag{35}$$

2.2.4 Contrast of retinal illuminance

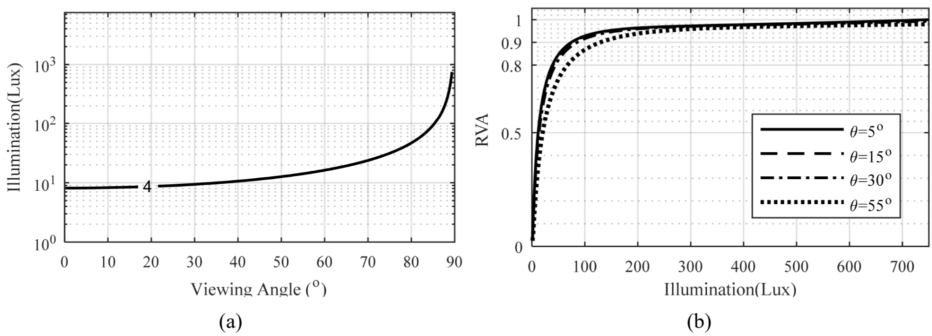
The contrast of retinal illuminance (CRI) is defined as the relative and absolute difference of the retinal illuminance for OC (ϵ_c) and that for the white paper (ϵ_w), that is

$$CRI = \frac{|\epsilon_c - \epsilon_w|}{\epsilon_w} = \frac{|\epsilon_c - L_a S|}{L_a S} \tag{36}$$

2.3 Comfort analysis

The acuity-concerned parameters, AVA and RVA, are simulated under different illuminations and viewing angles. As shown in Figure 3, where the contour line of AVA = 4 indicates the boundary of the comfort range.

Figure 3 Simulation of the visual acuity indices under different levels of illumination, (a) AVA index (b) RVA index



From Figure 3(a), the conclusion can be drawn from the AVA index that to assure the accurate vision, the illumination should be high enough. From Figure 3(b), if the illumination is relatively low, the RVA index is decreased dramatically as the diminution of the illumination. Ergonomic researches have revealed that viewing angle usually ranges from 5° to 55° while reading by self-adjusting the angle of the head and the books to achieve a higher quality of reading comfort (Yin, 2014; Ma, 2013). Thus, when the illumination is above around 130 Lux, the RVA index is relatively high (over 0.9) in all the viewing angles from 5° to 55°, and there is a relatively weak tendency that the RVA index alters as the illumination changes.

Moreover, six object colours (OCs) (listed in Table 1), which means the colour painted on the paper, are selected to simulate the reading comfort under the ambient illumination with different colour temperature (CCT).

Table 1 Objective colours for simulation

Colour	*CCT (K) (full brightness)*	*Categories*
Red (R)	2,165.8	Warm
Yellow (Y)	3,908.1	Warm
Green (G)	6,068.4	Neutral
Gray (W)	6,503.2	Neutral
Light blue (B)	9,317.8	Cool
Cyan (C)	12,841.8	Cool

Figure 4(a) shows the simulated RRI index and CRI index of the six OCs in Table 1 with different brightness printing on the white paper under different illuminations.

As shown in Figure 4(a), some conclusion can be drawn that,

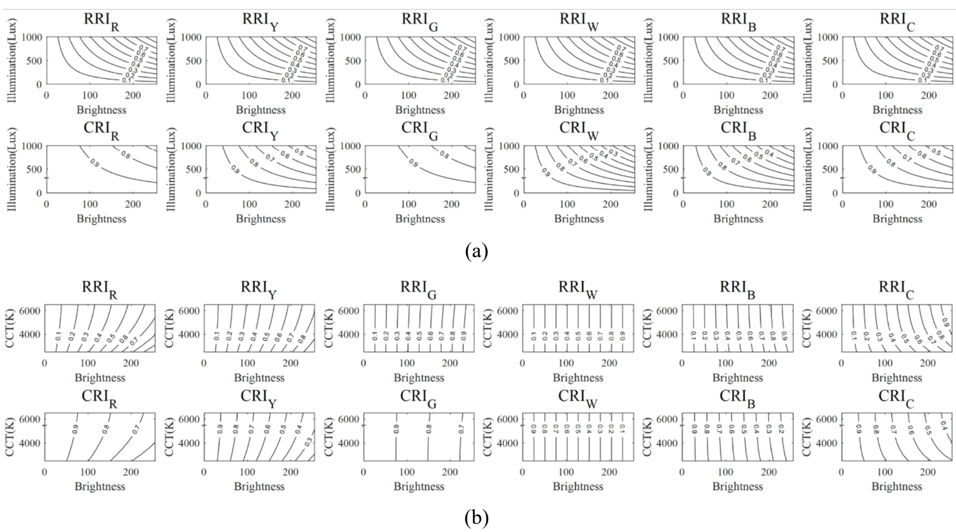
1 The higher the brightness of the OC is, the more likely that CRI index changes with the illumination change.

2 For all the OCs with the same brightness, the RRI index positively corresponds to the illumination while the CRI index negatively corresponds to the illumination.

3 Further analysis shows that the RRI index of the same brightness is directly proportional to the illumination.

Considering that the AVA index and RVA index are not taken the colour temperature into account directly, thus, only the RRI index and the CRI index are simulated. Figure 4(b) shows the simulated RRI index and CRI index of the six OCs in Table 1 with different brightness printing on the white paper under different colour temperatures.

Figure 4 Simulation results of CRI and RRI, (a) for illumination analysis (b) for colour temperature analysis



As shown in Figure 4(b), some conclusion can be drawn that,

1 The lower the brightness of OC is, the less likely that the RRI index and CRI change with the alteration of colour temperature.

2 For the warm OCs, the RRI index negatively corresponds to the colour temperature under the same brightness, while the CRI index positively corresponds to the colour temperature.

3 For the neutral OCs, the RRI index and CRI index are nearly independent as the colour temperature of the luminous environment changes.

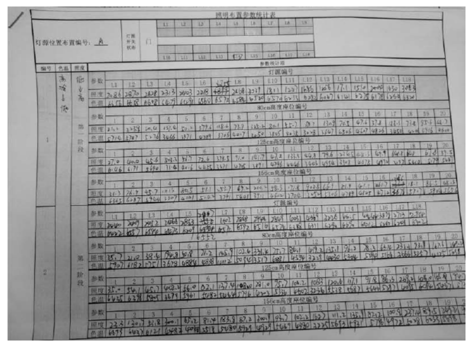
4 For the cool OCs, the RRI index positively corresponds to the colour temperature under the same brightness, while the CRI index negatively corresponds to the colour temperature.

2.4 Theoretical discussion

In short, from the discussions above, there is the best range of illumination over around 130 Lux of the luminance system, where the visual stimuli are strong enough to human's visual perception, the visual acuity is relatively reasonable, and the contrast will not be significantly decreased. Meanwhile, the recommended colour temperature is around that of natural light (5,000 K to 6,000 K).

Figure 5 Comfort evaluation experiments, (a) the rest rig (b) the record of the conditions (c) the participants taking the experiments

(a)



(b)

(c)

3 Experimental analysis

The quantitive mechanism cannot be founded in the entirely theoretical analysis for some subjective issues of the comfort. To study the issue more profoundly, a series of experiments were conducted at the comprehensive comfort test-rig in the State-Key Laboratory of Traction Power, China.

3.1 Experiment condition

The ambient luminous environment can be altered by adjusting the illumination and the colour temperature of the LED lighting system composed by 14 LED lights. The measuring point was mounted at the point of the middle seats at the front, middle, rear part of the experimental chamber (about 5 m $\times$ 3.3 m $\times$ 2.3 m) in a real train with a height of 0.8 m from the ground according to the current standard for daylighting design of buildings (GB/T 50033, 2013) utilised in China. Here is the parameters of the simulation and measuring system.

- Range of the simulated illumination: $<$750 Lux.
- Precision of illumination measurement: $\pm$4%.
- Range of the simulated CCT: 3,000 K–6,000 K.
- Precision of CCT measurement: $\pm$4%.

It should be noted that the control of LED lights is not infinite and continuous and the ambient luminous environment will affect the inner illumination and colour temperature. Thus, the value of the illumination and colour temperature cannot be specifically set.

The 20 participants were students from Southwest Jiaotong University, with the age of 23.8 $\pm$ 3.2. The reading material is the Chinese books with the recommended size of 10.5 pt and the font of ‘song’ for main texts.

3.2 Experiment process

Series of experiments were conducted by objectively measuring the luminous factors inside carriages and obtaining subjective evaluation from the subjectives. The main process of the experiment was,

1. The test personnel changed the ambient luminous environment (including illumination and the colour temperature) as well as tested the parameters of the current environment.
2. The participants were asked to be seated and simulate the travelling and reading experiments.
3. The participants were required to tell his/her subjective evaluation (by a questionnaire, in which only the subjective evaluation of the luminous environment is required) about reading comfort 5 minutes later and were suggested to take a rest under the natural luminous environment to minimise the impact of the current condition to the next condition.

4 Redid the process 1 to 3 to gain all the evaluation of all the participants under all the conditions shown in Figure 6.

3.3 Data processing

A fuzzy algorithm, in which the inputs are illumination (CI) and colour temperature (CT), and the outputs are reading comfort (CC) is established.

The data space has been divided into some sub-blocks with different ranges of illumination and colour temperature. The pattern of the bilateral Gauss membership function of the inputs is selected as manifested in equation (37), with taking the simulation and measuring parameters into consideration.

$$f_i(x) = \begin{cases} e^{-\frac{(x-c_1)^2}{2\sigma^2}} & x < c_1 \\ 1 & c_1 \le x \le c_2 \\ e^{-\frac{(x-c_2)^2}{2\sigma^2}} & x > c_2 \end{cases} \tag{37}$$

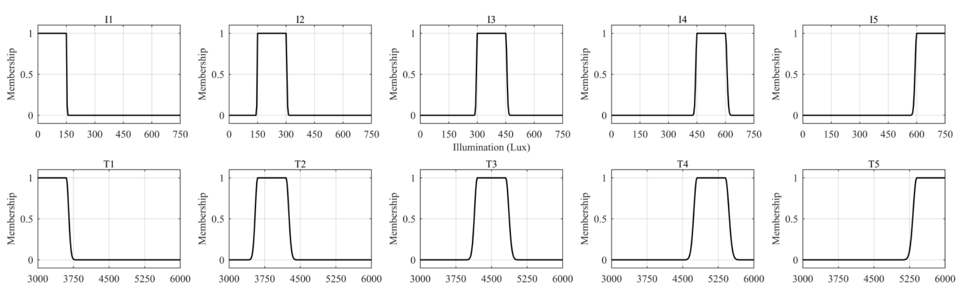
where x is the value of illumination (or colour temperature); c_1, c_2 are the minimum value and the maximum value of the illumination (or colour temperature) range, respectively; σ_1 and σ_2 are the standard error of the measurement. If the distribution of measurement error is Gaussian and the confidence interval is selected as 97.3%, then the value of σ_1 and σ_2 can be estimated, namely,

$$\sigma_1 = \frac{4c_1}{300} \tag{38}$$

$$\sigma_2 = \frac{4c_2}{300} \tag{39}$$

The membership functions of the inputs are shown in Figure 6 within the selected length of the illumination range is 150 Lux, and the length of the colour temperature range is 600 K.

Figure 6 The membership function of inputs



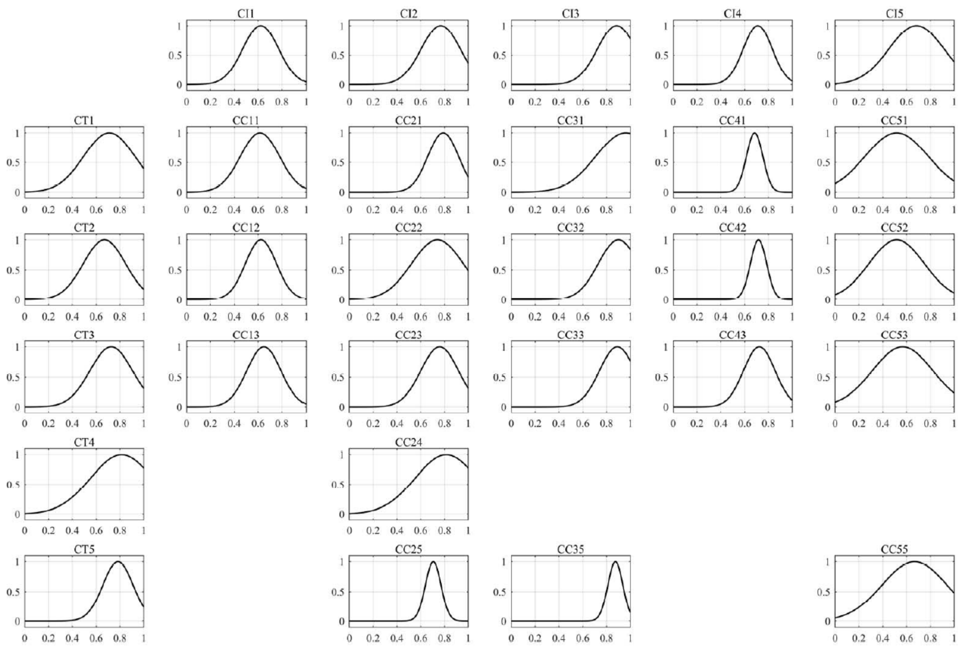
Then the membership functions of the outputs can be selected. The evaluation of the reading comfort can be quantified mathematically. The evaluation results can be defined as $E_{ij} = [e_1, e_2, e_3, e_4, e_5]$ and e_1 to e_5 means the percentage of passengers who feel 'very comfortable', 'comfortable', 'moderate', 'uncomfortable' and 'very uncomfortable', respectively.

Supposing that under a particular circumstance, the quantitative evaluation results are Gaussian (Fang et al., 2011), the membership function of outputs can be expressed as

$$g_{ij}(x) = e^{-\frac{(x-c)^2}{2\sigma^2}} \tag{40}$$

Figure 7 shows the membership function for comfort evaluation of illumination (CI), colour temperature (CT) and a combination of the two (CC). Additionally, some blocks are invalid because of the adjusting ability of the luminous simulation system.

Figure 7 The membership functions



Notes: x-axis represents the evaluation and y-axis represents the membership function.

Then the fuzzy rules can be established. There are three patterns of fuzzy rules of the fuzzy algorithm, those are,

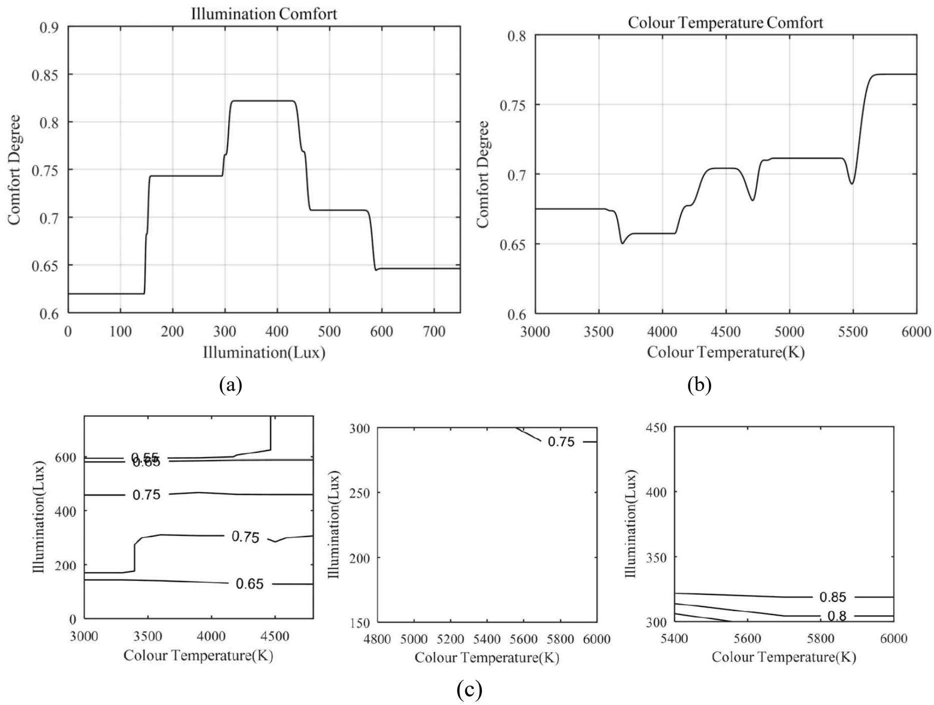
1 For the comfort of illumination: If Illumination is I_i then illumination comfort is CI_i.

2 For the comfort of colour temperature: If colour temperature is T_j then colour temperature comfort is CT_j.

3 For comprehensive comfort: If illumination is I_i and colour temperature is T_j then comprehensive comfort is CC_{ij}.

The simulation result of the reading comfort is shown in Figure 8.

Figure 8 Comfort evaluation results, (a) illumination comfort (b) colour temperature comfort (c) comprehensive comfort



3.4 Discussion

From Figures 8(a) and 8(b), the conclusion can be drawn that,

1 The best range of the illumination for the reading passengers is around 175 to 450 Lux.

2 The best range of the colour temperature contains the range of 5,500 to 6,000 K.

3 The passengers' riding comfort is more likely affected by the illumination change than colour temperature change.

From Figure 8(c), the optimum range of comprehensive comfort is much smaller than the range defined by the optimum illumination comfort and optimum colour temperature comfort. It can be concluded that,

1 If the illumination is relatively low, the passengers will prefer a warmer-coloured light. Meanwhile, when the illumination is higher than the optimum range, the comprehensive comfort will be more likely of decreasing trend under the warm illuminance.

2 The optimum illumination range of the comprehensive comfort will be narrowed in the range of 300 Lux to 450 Lux for all the colour temperatures.

Moreover, there are some similarities and differences between this research and some other researches, some comparisons are listed below,

1 The results of the optimum illumination range in this study is approximatly similar to the results of Lege et al. (2017) (300 Lux to 500 Lux) in Japan while there is a distinction between this study and the study of Avcı and Memikoğlu (2017) in Turkey, in which the favouriable illumination is 500 Lux. Thus, the differece in the experiments results between East Asian and Turkey people implies that optimum range may differ from the physical conditions.

2 In researches of Su et al. (2013b), the optimum range of illumination is 150 Lux to 300 Lux when the passengers are not reading, which is smaller than the range that is optimum for reading passengers.

3 According to the *Standard for Lighting Design of Buildings* in China (GB 50034, 2013), the colour temperature in the reading room is around 3,300 K to 5,300 K, which is smaller (warmer) than the results in this study. Moreover, the optimum range of illumination in this study is 300 Lux to 450 Lux on the plane at the height of 0.8 m, which covers the recomended illumination (300 Lux) in GB 50034-2013.

Thus, the range of the illumination and colour temperature should be properly, customised and even individually-controllably decided in Chinese high-speed trains to meet more passenger's needs.

4 Conclusions

By theoretical analysis and experimental analysis, the mechanism of the effect of the luminous environment on the passengers of the Chinese high-speed train has been studied. Some conclusions can be drawn as below.

1 The illumination at the height of 0.8 m from the ground should be higher than 175 Lux for gaining the adequate visual stimuli and visual acuity while reading on the train. Meanwhile, the illumination should be less than 450 Lux to ensure the contrast decrease by the unreasonably high illumination to the degree that affects the passengers reading comfort.

2 The colour temperature of the luminous system is recommended to be approximately natural (around 6,000 K) for reading passengers, especially for high illuminated environments. Meanwhile, the warm coloured lights are also preferred when the illumination is relatively low (around 175 Lux to 300 Lux).

3 The passengers' riding comfort is more likely affected by the illumination change than colour temperature change.

However, some issues will be further studied. First, the mechanism of colour temperature where there is over 6,000 K has not been validated by the limitation of the experimental environment. Second, these conclusions may not be applicable in real situations because reading is only one of the activities of the train passengers, that means the comfortable luminous environment may be uncomfortable for other passengers. Last, the optimum range of the luminous factors may be altered by the human's subjective factors and any other factor not taken into consideration in this research. To achieve a higher degree of riding experience, the further physiological and psychological studies needs to be conducted in the future to reveal more characteristics concerning human's reactions under different luminous environments.

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