Color Characteristics of Four-Color Samples in the Foggy Environment under Different Lighting Conditions

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Abstract. Traffic signs should provide clear signals for drivers and passengers under various environmental and geographic conditions. In foggy weather, the signal will be disturbed due to light scattering, which will cause obstacles to recognition. This study simulated a foggy environment in the laboratory, used a standard color card as the target, and introduced a colorimeter to record the color coordinates, then calculated the color difference and analyzed the four-color samples’ color properties in different lighting conditions. We found that as the relative visibility increases, the chromatic aberration of the sample will gradually decrease under different lighting conditions and reach zero when the relative visibility is higher than 70%. We found that the green and blue samples have better color coordinate retention capabilities than the fog’s red and yellow. We compared all tested light sources’ performance, and the results showed that 3000K LED and incandescent lamps are better than other light sources. This study will provide a data basis for the study of traffic safety and accident prevention.

Keywords: Fog, LED, standard color card, color discrimination.

1. Introduction

Fog can be hazardous to traffic systems, including roads, ports, and airports. In dense fog, driving becomes difficult and even dangerous. Not only visibility but also color discrimination can be seriously affected. As a result, there may be trouble observing traffic signs, leading to injuries and lives lost.

Studies on lighting and vision show critical and practical significance in a foggy environment. Most of them focused on light sources’ characteristics in previous research, for instance, brightness [1-3], dominant wavelength [2-6], visual perception, and light propagation properties [5-9]. Some researchers involved human subjects in evaluating their perception of object color in dense fog or simulated foggy pictures [10-13]. However, few researchers paid attention to the properties of the non-self-luminous target. This study calculated and measured the color difference to discuss color discrimination without a human's subjective influence in a foggy environment. We simulated a foggy environment to investigate four-color samples' color differences under different illuminating conditions. We believe this result can provide a data basis for improving transportation safety.
2. Methods

2.1. Experimental setup
Figure 1 shows the experimental setup. We made the dark box (1.5m in length, 0.7m in width, 1.2m in height) with wood and plastic boards, installing two acrylic windows on both ends. The inner surface of the box, except the windows, was painted black to prevent light reflection. We set a standard color card (Munsell Color Checker Mini Passport) and an illuminance meter (ST-85 from PEIFBNU) in parallel at the right end of the box and placed light sources and a color luminance meter (CBM-8 from EVERLINE Corporation) at the other end, and installed an ultrasonic humidifier outside the box, with its nozzle connected to an opening of the box.

![Schematic diagram of the experimental setup (Top View).](image)

Figure 1. Schematic diagram of the experimental setup (Top View).

We utilized an incandescent lamp and four white light-emitting diodes (LEDs) of different color temperatures (3000K, 4600K, 6300K, and 6500K) to provide uniform illumination on the target. Figure 2 shows the relative spectral energy distributions of these light sources.

![Relative spectral energy distributions of the light sources.](image)

Figure 2. Relative spectral energy distributions of the light sources.

2.2. Fog concentration and relative visibility
The humidifier uses ultrasound (1.7MHz) to resonate water surface and generate a tiny droplet, ranging in about 10μm, accords with natural fog [11]. We used the humidifier to simulate the foggy environment, which was uniform, stable, and controllable. We determined the fog concentration by measuring the transmitted light from the light source with the illuminance meter and defined the transmittance of light by the following equation:

\[ T = \frac{E}{E_0} \]  
\[ P = 1 - T \]  
\[ V = 1 - \frac{P}{P_0} \]
E' is the illuminance value of different foggy conditions, and \( E_0 \) means the initial illuminance value without fog. We used the equation to define the fog concentration and (3) to express the relative visibility. \( P_0 \) is the maximal fog concentration. \( P' \) is the current concentration. \( V \) is the relative visibility, which ranged from 0% to 100%.

2.3. Chromaticity measurements

We employed a standard color card, Munsell Color Checker Mini Passport, as the observation target. This study selected four-color samples (blue, green, red, and yellow) for the experiment, commonly used in display technologies and color theory. Table 1 shows the CIE \( L^*a^*b^* \) values of color samples, and every size is 1 cm².

| Color Sample | \( L^* \) | \( a^* \) | \( b^* \) |
|--------------|---------|---------|---------|
| Blue         | 28.778  | 14.179  | -50.297 |
| Green        | 55.261  | -38.342 | 31.37   |
| Red          | 42.101  | 53.378  | 28.19   |
| Yellow       | 81.733  | 4.039   | 79.819  |

** CIE \( L^*a^*b^* \) values use Illuminant D50 2-degree observer.

In the experiment, the fog dissipated relatively fast, and it was hard for human subjects to distinguish the color in a relatively short time. Other factors like psychological state or vision condition would also harm the measurement. We measured the color coordinates for further calculation of color difference, chose the viewing angle of 0.1° according to the experimental setup and the standard color card size, adopted the CIE 1976 LAB color space for data analysis, and employed a standard color card, Munsell Color Checker Mini Passport, as the observation target. It was waterproofed and moisture-proofed.

2.4. Experimental Process

We recorded the initial illuminance value of light sources and color coordinates of color samples without fog, switched on the humidifier, and kept working to generate fog. The working time of the humidifier under different illuminating conditions was the same. The time was long enough for the fog to reach the maximum concentration and illuminance to reach the minimum value. We recorded \( E' \) and color coordinates simultaneously with the fog dissipating and programed the color luminance meter for automatic measurement in advance.

The formula for converting tristimulus value to XYZ to Lab is as follows:

\[
L^* = 116f(Y/Y_0) - 16 \tag{4}
\]

\[
a^* = 500[f(X/X_0) - f(Y/Y_0)] \tag{5}
\]

\[
b^* = 200[f(Y/Y_0) - f(Z/Z_0)] \tag{6}
\]

\[
f(t) = \begin{cases} 
(29/6)^2 t / 3 + 16/116, & t \leq (6/29)^3 \\
1/3, & t > (6/29)^3 
\end{cases} \tag{7}
\]

\[
f(t) = \begin{cases} 
(29/6)^2 t / 3 + 16/116, & t \leq (6/29)^3 \\
1/3, & t > (6/29)^3 
\end{cases} \tag{8}
\]

Among them, \( X_0, Y_0, Z_0 \) are white reference point CIEXYZ tristimulus values. After the experiments, the CIELAB was adopted as a calculation model to process the recorded color
coordinates. We worked out the color differences and evaluated the effect of fog on color discrimination numerically. The chromatic calculations were as follows:

\[ \Delta L^* = L^*_{sp} - L^*_{st} \tag{9} \]
\[ \Delta a^* = a^*_{sp} - a^*_{st} \tag{10} \]
\[ \Delta b^* = b^*_{sp} - b^*_{st} \tag{11} \]

\( L^*_{sp}, a^*_{sp}, \) and \( b^*_{sp} \) refer to the values measured in a foggy environment, while \( L^*_{st}, a^*_{st}, \) and \( b^*_{st} \) refer to the values obtained without fog. The following equation then figured out the \( \Delta E^*_{ab} \):

\[ \Delta E^*_{ab} = (\Delta L^*^2 + \Delta a^*^2 + \Delta b^*^2)^{1/2} \tag{12} \]

3. Result and analysis

3.1. The difference between color samples and background in a fog environment

Figure 3 shows the color differences between four color samples and background (black) under different illuminating conditions. We regarded the LAB value of black as typical values \( (L^*_{st}, a^*_{st}, \text{and } b^*_{st}) \) and discussed the ability of color samples to be distinguished from a black background. As the fog concentration increased, all color samples approached the sample level similar to the background. When fog concentration reached a certain level, it was hard to distinguish colors from each other and black. Meanwhile, the red color had the most significant value of \( \Delta E^*_{ab} \) among four colors when fog became more solemn, and the relationship of other colors was not that clear to conclude a rule. So, it was more likely to recognize red from the black background when fog is not heavy.

Figure 3. Color difference of four-color samples and background in fog environment.
We found that the value of $\Delta E_{ab}$ dropped suddenly in some situations, while others slowly decreased during the fog dissipating course. The reasons were related to scattering mode changing, the diameter of water drops, and waterproof film. Comparing five lamps, we found that the incandescent lamp had the smallest range of $\Delta E_{ab}$, while 3000K LED took second place. Other lamps had an even bigger range of $\Delta E_{ab}$. The reason may have something to do with the spectral energy distribution and the color temperature of lamps.

3.2. The relationship between color difference and relative visibility under an incandescent lamp

Figure 4 shows the dynamic change of color differences of four-color samples in the situation of an incandescent lamp. This part intended to discuss the ability of color samples to maintain their color coordinates. As the relative visibility increases, the $\Delta E_{ab}$ of the red sample gently decreases at first, then drops to zero abruptly when the relative visibility is around 50-60%. The change of green samples is similar. By contrast, the $\Delta E_{ab}$ of the blue sample seems to decline to zero slowly. Concerning the yellow sample, the $\Delta E_{ab}$ remains at the near-zero level except when the relative visibility is below 10%. The color differences between all samples reach zero when the relative visibility rises to about 70%.

![Figure 4. Color difference of four-color samples in the situation of an incandescent lamp.](image)

When fog dissipates, the diameter of water drops is changing as well. Some water droplets volatilize, and the diameter decreases. Some condense, and the diameter increases. Both effects helped to decrease the absorption of light. Probably, both effects reached the threshold around relative visibility 60%. From the phenomenon above, we divided the pattern of the dynamic change of $\Delta E_{ab}$ into two categories: step change and slope change. All color differences start from a relatively high value and go down to zero when the relative visibility reaches a high level of 70%.

3.3. The color shift of different color samples and illuminating conditions

Figure 5 shows the direction of color shift on the CIE1931 XY chromaticity diagram in the situation of five light sources. The start points of arrows indicated the color coordinates recorded without fog, while the endpoints were the color coordinates recorded under the maximum concentration of the fog.

Considering the situation of the incandescent lamp, we found that the length of arrows represents the full-color shift of color samples and as the fog concentration increasing, the direction of color shifts of blue, green, and red samples was to the yellow area of the color diagram, while that of the yellow sample shifted to the white area. Color coordinates of four samples moved to the same small area, making it difficult to distinguish colors.
Figure 5. Color shift of four-color samples in the situation of lamps.

3.4. Maximum values of different color samples and illuminating conditions

Figure 6. Maximum values of color difference under different situations.
Figure 6 exhibits the maximum values of color differences under all situations in the experiment. From the graph, we found that the maximum $\Delta E_{ab}^*$ in the incandescent lamp and the 3000K LED lamp was lower than other lamps. The relationship between color samples is alike: red > green > blue > yellow. Meanwhile, the data of 6300K LED resembles that of 6500K. Both have greater $\Delta E_{ab}^*$ of red and yellow samples and a smaller difference in green and blue ones. The color differences of samples regarding 4600K LED is quite unlike the others. As shown, the maximum $\Delta E_{ab}^*$ of the blue sample is far bigger than the others.

Figure 7 exhibits the maximum values of lightness differences under different situations. From the picture above, there were two significant differences. First, yellow under incandescent lamps' lightness exceeded the other colors while under LED lamps kept the lowest value among the four-color. Second, the lightness of the red sample under LED lamps was higher than those of other colors. The phenomenon above may have relations with color temperature and relative spectral energy distribution of light sources.

The color temperature of a typical incandescent lamp is close to 3000K. Also, the relative spectral energy distributions of incandescent lamps and the 3000K LED have something in common: energy is low in short wavelength and high in long wavelength. That is why the color differences of samples under the conditions of these two lamps are quite alike. The difference is that the energy of 3000K LED is lower than that of the incandescent lamp in most of the wavelengths, especially in wavelengths above 620nm, which makes the values of $\Delta E_{ab}^*$ under 3000K LED smaller than those under an incandescent lamp.

The relative spectral energy distributions of LED lamps in this study are similar to each other. However, with the color temperature ascending, the energy distribution of green and blue light becomes more assertive, and that of yellow and red light becomes weaker. Correspondingly, the green sample's color differences seem to stay low, even decreasing tendency, while those of yellow and red samples are greater and tend to increase. The performance of the blue sample is exceptional. It has a smaller $\Delta E_{ab}^*$ in both low and high color temperature and a more excellent middle color temperature value. Further analysis is needed. Considering all the situations, 3000K LED and incandescent lamps have a better capability for color identification. In agreement with previous studies, the yellow or low-color-temperature light sources have good transmittance properties in fog conditions.

According to previous research, green and blue lights have low transmittance properties in fog conditions when applied to self-luminous targets. In contrast, green and blue color samples, non-self-luminous targets, show a more stable performance than the other colors as their color shift is relatively small. Red and yellow color samples have low properties in fog conditions, while red and yellow lights have better transmittance properties. When fog is not heavy enough, the red color sample was more likely to be recognized than other colors. Therefore, the blue and green color may be better...
choices for the background color of non-self-luminous traffic signs, while red and yellow may be better choices for self-luminous signs.

4. Conclusion
This manuscript discussed color discrimination by measuring four-color samples' color differences under different illuminating conditions in a simulated foggy environment. The results are as follows:
(1) As the relative visibility increases, the color differences of samples decrease gradually or abruptly under different illuminating conditions and reach zero when the relative visibility is above 70%.
(2) Comparing the performance of all light sources under test, 3000K LED and the incandescent lamp exceeded the others.
(3) Green and blue samples have a better ability to maintain their color coordinates than red and yellow in fog.
(4) Red sample is more likely to be identified in a thin fog environment than other colors. In heavy fog, the person cannot recognize all color samples from the black background.
In this study, we found that color temperature and relative spectral energy distribution of light sources were the reasons for the study's phenomenon. We would investigate more factors and experiments in the next research. The results obtained in this research provide preliminary references for traffic signs and signals and automobile lighting design.

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References
[1] Kurniawan, B.A., Nakashima, Y. & Takamatsu, M., Analysis of the visual perception of light emitting diode brightness in dense fog with various droplet sizes, OPT REV. 15, (2008) 166-172.
[2] Takamatsu, M. & Nakashima, Y., Brightness Perception of Light Source Colors in Dense Fog, OPT REV. 8, (2001) 198-202.
[3] Tang, Y., Song, Y., Zhou, X., Chen, L. & Liu, M., Study of the Visibility in Simulated Foggy Environment, China Illuminating Engineering Journal. 6, (2015) 71-75, 136.
[4] Zaini, MFB, Kurniawan, B.A., Nakashima, Y. & Takamatsu, M., Perceived Brightness and Saturation of Color LED Light in Dense Fog at Night Time, Journal of Light & Visual Environment. 33 (2), (2009) 107-109.
[5] Kurniawan, B. A., Nakashima, Y., Takamatsu, M. & Kidoh, Y., Visual Perception of Color LED Light in Dense fog, Journal of Light & Visual Environment. 31(3), (2007) 152-154.
[6] Sirohi, R. S., Effect of fog on the color of a distant light source, Journal of Physics D Applied Physics. 3 (1), (1970) 96-99.
[7] Lv, Z. & Xu, T., Determination of optimum penetration wavelength for fog lights, J. Appl. Opt. 29 (4), (2008) 530-532, 547.
[8] Yuan, H., Zhou, X., Zhang, Z. & Xu, F., Study the Transmittance Properties of Light Sources Under Simulated Hazy Condition, International Conference on Applied Physics, System Science and Computers. Springer, Cham. (2017) 263-271.
[9] Babaria, B. R., Alvarez, T. L., Bergen, M. T. & Servatius, R. J., Transmission of light in a synthetic fog medium, Bioengineering Conference, 2004. Proceedings of the IEEE, Northeast. IEEE. (2004) 23-24.
[10] Hagedorn, J., & D.Zmura, M., Color appearance of surfaces viewed through fog, Perception, 29 (10), (2000) 1169-1184.
[11] Takamatsu, M., & Nakashima, Y., Apparent Color of 10 Test-Color-Cards in Dense Fog, IEEJ Transactions on Fundamentals and Materials, 121 (9), (2001) 815-822.
[12] NAKASHIMA, Y., & TAKAMATSU, M., Appearance of Object Colors in Dense Fog: Shift of Perceived Munsell Value and Chroma, Journal of Science and Technology in Lighting, 86 (2), (2002) 107 (in Japanese).

[13] Nakashima Y. and Takamatsu M., Appearance of Object Colors in Dense Fog: Shift of Perceived Munsell Value and Chroma, J. Light & Vis.Env., Vol. 25, No.2, pp.23-30, 2001.

[14] Mukaigawa, Y., Yagi, Y. & Raskar, R., Analysis of light transport in scattering media, Computer Vision and Pattern Recognition. IEEE. (2010) 153-160.

[15] Guan, X. & Zhao, H., The Experimental Research for Visual Visibility of Electric Light Source in Mist, China Illuminating Engineering Journal. 6 (2013) 36-41.