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Posted Date: 26 July 2023

doi: 10.20944/preprints202307.1777.v1

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Experimental Study on Chromaticity Control in Visible Light Communication Systems

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Abstract: In order to apply visible light communication systems in different scenarios, this article utilizes an excellent temperature adjustable light source mixed with RGB LEDs, and applies it in a visible light communication system. It utilizes color division multiplexing technology to achieve three-channel communication, thereby improving the communication bandwidth of the system. The communication system adopts three constant current driving circuits to control the duty cycle of Pulse Width Modulation (PWM) of each channel, thereby changing the proportion of RGB LEDs, and obtaining different color temperatures to achieve the purpose of color control for mixed color LEDs. The experimental results show that when adjusting the color temperature, the change in luminous flux is very small, with fluctuations of less than 2.24%; When adjusting the brightness, the color temperature fluctuation is within 40K, which is less than the 50K color temperature limit that the human eye can distinguish, and the average color temperature error is 0.609%; Color tolerance less than 5.5×10^{-3} indicates good dimming effect, and the communication performance of the system is better in the high color temperature range, which is significantly superior to the low color temperature range. When the error rate is below 3.8×10^{-3}, the total modulation bandwidth of the three channels reaches 11.7 MHz.

Keywords: adjustable color temperature; RGB LEDs; PWM; visible light communication;

1. Introduction

As a white LED with dual functions of lighting and communication, in addition to the communication performance of the light source, the impact of the color of the light source on the human eye should be considered [1,2]. Lighting environment can bring a good psychological, physiological, and visual impact to people [3,4]. The color temperature of the light source has a significant impact on the human nervous system [5]. Cold colored light sources can easily stimulate the nervous system, and in high color temperature environments, a person's heart rate and pulse accelerate, blood pressure increases, and mental excitement occurs. On the contrary, warm colored light sources have effects such as soothing emotions, reducing stress, lowering heart rhythm and pulse [6]. In terms of psychological perception, low color temperature light sources (warm color light) make people feel warm, while high color temperature white light (cold color light) makes people feel cold [7]. In order to achieve dynamic changes in LED color temperature, it is necessary to quantitatively control the chromaticity of the light source. Studying LED light sources with adjustable color temperature in visible light communication systems has certain significance. Adjusting the color temperature of LEDs according to different environments can make people feel comfortable with the light environment and create a healthy lighting environment. In general, the color temperature range of indoor lighting is 3000K~6500K [8]. Use light sources with different color temperatures in different situations to meet people's psychological and physiological needs. So, how to make the color temperature of the light source in visible light communication systems adjustable and control the chromaticity is currently a hot research topic.

There have been studies on the use of multi-color LEDs for information transmission in visible light communication systems. In 2012, Kottke C et al. used Wavelength-division multiplexing

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technology in the visible light communication system to realize the data transmission experiment of RGB LEDs light source with a communication rate of up to 1.25Gbps under 1000lx illumination [9]. In 2014, G Cossu et al. realized a bidirectional visible light communication system by using Wavelength-division multiplexing. The uplink communication rate of the system is 5.6Gbps, and the uplink communication rate is 1.5Gbps [10]. The following year, the team achieved four channels of information transmission in a visible light communication system, and when the error rate of each channel was below 3.8×10^{-3}, a data rate greater than 5 Gbps was achieved for the downlink within a distance of 1.5m~4m indoors, and communication greater than 1.5 Gbps was achieved for the uplink [11]. In 2015, Ke X Z et al. constructed an RGB LEDs visible light communication video transmission system and completed an experiment on video data stream transmission at a transmission rate of 1.5 Mbps [12]. In 2018, Bian R et al. realized a 10.2Gbps three channel visible light communication experiment using RGB LEDs and Wavelength-division multiplexing [13]. The following year, the team used four different colored LEDs as light sources and OFDM modulation method to complete an experiment on 15.73Gbps VLC reliable transmission on a 1.6m link [14]. In 2022, Qiu et al. used three LEDs and five micro-LEDs and Wavelength-division multiplexing technology to successfully achieve a visible light communication experiment with a total communication rate of 25.20 Gbps when the communication distance is 25 cm [15]. In the field of visible light communication, multi-channel visible light communication systems using multiple monochrome LEDs have achieved high communication rates, but there is no color control mechanism. The color of the light emitted by multiple LEDs poses a certain threat to human eyes [16,17]. Research shows that the color and brightness of the light source have an impact on the adjustment ability of the ciliary muscle of the human eye [18], which can cause visual fatigue and discomfort and easily lead to myopia.

In the indoor environment, visible light communication not only realizes the communication function, but also meets the lighting requirements. It is also suitable for some special occasions, such as bars and studios, where the light source is not only white light, but also requires adjustable color and chroma. Therefore, the multi-color transmission system should also consider the light mixing and chroma control of the light source. This article conducts experiments and analysis on the chromaticity control of light sources in RGB LEDs visible light communication systems. By controlling the duty cycle of PWM in each channel and changing the proportions of red, green, and blue LEDs respectively, different color temperatures can be obtained to achieve the purpose of controlling the chromaticity of mixed color LEDs.

2. Theoretical basis

To analyze the color rendering of LED, the Gaussian mathematical model (Y-model) proposed by Yoshi Ohno et al. is in good agreement with the actual LED spectral distribution and has been widely recognized. This model can be represented as [19]:

$$S_{LED}(\lambda,\lambda_0,\Delta\lambda_{0.5}) = Y_c\frac{g(\lambda,\lambda_0,\Delta\lambda_{0.5})+2g^5(\lambda,\lambda_0,\Delta\lambda_{0.5})}{3}, \tag{1}$$

In the formula, $g(\lambda,\lambda_0,\Delta\lambda_{0.5}) = \exp[-((\lambda-\lambda_0)/\Delta\lambda_{0.5})^2]$; λ is the wavelength; Y_c is the spectral power at peak wavelength λ_0; $\Delta\lambda_{0.5}$ is the half peak width.

The tristimulus value of a light source refers to the basic optical characteristics of the light source, usually used to describe and measure the color of the light source. According to the spectral mathematical model of LED, the tristimulus values X, Y, and Z of the light source to be tested can be calculated, and the calculation formula is [20]:

$$\begin{cases} X = K_m\int_{380}^{780} S(\lambda)\overline{x}(\lambda)d\lambda \\ Y = K_m\int_{380}^{780} S(\lambda)\overline{y}(\lambda)d\lambda \\ Z = K_m\int_{380}^{780} S(\lambda)\overline{z}(\lambda)d\lambda \end{cases}, \tag{2}$$

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In the formula, K_m=683lm/W , as the constant; $S(\lambda)$ is the relative spectral power distribution; $\bar{x}(\lambda)$, $\bar{y}(\lambda)$ and $\bar{z}(\lambda)$ are the color matching function, which is the average data of the CIE 1931 standard observer, also known as the spectrum triple stimulation function [21].

In actual calculation, the CIE 1931 standard chromaticity tristimulus value of the light source to be tested is obtained by using the method of discrete summation and approximate integration calculation. The expression can be expressed as:

$$\begin{cases} X = K_m \sum_{380}^{780} S(\lambda)\bar{x}(\lambda)\Delta\lambda \\ Y = K_m \sum_{380}^{780} S(\lambda)\bar{y}(\lambda)\Delta\lambda \\ Z = K_m \sum_{380}^{780} S(\lambda)\bar{z}(\lambda)\Delta\lambda \end{cases}, \quad (3)$$

In the formula, $\bar{x}(\lambda)$, $\bar{y}(\lambda)$ and $\bar{z}(\lambda)$ can be determined by looking up tables, and the spectral sampling interval of $\Delta\lambda$ =1 is often taken.

According to the obtained light source three stimulus values, the corresponding color coordinates can be found. After the normalization of X, Y ,and Z ,the color coordinates x, y and z of the light source to be measured can be obtained:

$$\begin{cases} x = \frac{X}{X+Y+Z} \\ y = \frac{Y}{X+Y+Z} \\ z = \frac{Z}{X+Y+Z} \end{cases}, \quad (4)$$

In lighting systems, color temperature is a physical quantity used to define the chromaticity of a light source, which can measure the lighting quality of the light source. The relevant color temperature of the light source can be calculated from the chromaticity coordinates, and the formula for calculating the color temperature is as follows [22]:

$$T = -437n^3 + 3601n^2 - 6861n + 5514, \quad (5)$$

In the formula, $n = \frac{x-0.3320}{y-0.1858}$; x , y is the color coordinate.

The color index is a parameter to evaluate the degree to which the light source restores the true color of an object. It is generally believed that under natural light, the color presented by objects is the most authentic, with a color index of 100. The color index of the light source for a standard sample can be expressed as [23]:

$$R_i = 100 - 4.6\Delta E_i, \quad (6)$$

In the formula, ΔE_i is the color difference of the sample under the reference light source and the light source to be tested, which can be obtained from the chromaticity coordinates.

The average Color index of the light source for color samples 1 to 8 is called the general color index R_a:

$$R_a = \frac{1}{8}\sum_{i=1}^{8} R_i, \quad (7)$$

3. Research on RGB LED dimming

3.1. Dimming method and calculation method

Dimming technology has become an important aspect of LED driving technology, and there are three commonly used LED dimming methods: DC dimming, PWM dimming, and thyristor dimming

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[24]. When the current is too small, the thyristor will disconnect, making the dimming effect unstable and not suitable for use in visible light communication systems [24]. DC dimming is achieved by changing the driving peak current of the LED to change the luminous flux. This dimming method can affect the chromaticity shift and color temperature change of the LED [25]. The PWM dimming method is achieved by changing the duty cycle of the LED light source, thereby changing the average luminous flux. The dimming performance is flexible and can accurately control the luminous flux, thereby accurately controlling the brightness change of the LED and reducing the impact of current changes during amplitude modulation on the stability of the light source [26]. In engineering practice, the color difference caused by PWM dimming is often not considered [27,28].

In the PWM dimming method, the peak value of the driving current remains unchanged, and the LED is dimmed by adjusting the duty cycle of the PWM. The expression is as follows:

$$I_{avg} = I_{peak} \cdot D, \tag{8}$$

In the formula, I_{avg} represents the effective value of the driving current, I_{peak} represents the magnitude of the driving peak current, and D represents the duty cycle of PWM.

For the convenience of calculation, it is usually assumed that the PWM duty cycle of the input driver module is directly proportional to the luminous flux output by the light source [29], which satisfies:

$$\Phi = D\Phi_{Max}, \tag{9}$$

In the formula, D is the duty cycle of the input PWM signal, $D < 1$; Φ_{Max} is the maximum output luminous flux; Φ is the luminous flux of the output signal.

According to Glassman's law of color mixing, there is a three-color mixing output luminous flux formula [30]:

$$\Phi = D_r\Phi_r + D_g\Phi_g + D_b\Phi_b, \tag{10}$$

In the formula, D_r, D_g, and D_b are the input duty cycle of PWM; Φ_r, Φ_g and Φ_b are the maximum output luminous flux of each light source; Φ is the output luminous flux of the mixed light.

In the CIE-1931 standard colorimetric system, it is specified that the stimulus value Y is equal to the luminous flux, so in the following text, it can be changed to Y. According to the principle of color mixing and the CIE 1931 color coordinate calculation method, the color coordinates after mixing with three light sources should meet [31,32]:

$$x = \frac{R_r D_r x_r + R_g D_g x_g + R_b D_b x_b}{R_r D_r + R_g D_g + R_b D_b}, \tag{11}$$

$$y = \frac{R_r D_r y_r + R_g D_g y_g + R_b D_b y_b}{R_r D_r + R_g D_g + R_b D_b}, \tag{12}$$

In the formula, x and y represent the color coordinates of a mixed light source consisting of three types of light sources; (x_r, y_r), (x_g, y_g) and (x_b, y_b) represent the color coordinates of red, green, and blue LEDs respectively; $R_r = \frac{Y_r}{y_r}$, $R_g = \frac{Y_g}{y_g}$ and $R_b = \frac{Y_b}{y_b}$ represents the sum of the three stimulus values of the light source under full current operation; D_r, D_g and D_b respectively represent the PWM input duty cycle of red, green, and blue LEDs.

From equations (10) to (12), the duty cycles of the three channels can be obtained as follows:

$$D_r = \frac{(y_g - y_b)(x_b - x) + (y - y_b)(x_g - x_b)}{(y_g - y_b)(x_b - x_r) + (y_r - y_b)(x_g - x_b)} \cdot \frac{y_r Y}{y Y_r}, \quad (13)$$

$$D_g = \frac{(y_b - y_r)(x_r - x) + (y - y_r)(x_b - x_r)}{(y_b - y_r)(x_r - x_g) + (y_g - y_r)(x_b - x_r)} \cdot \frac{y_g Y}{y Y_g}, \quad (14)$$

$$D_b = \frac{(y_g - y_r)(x_r - x) + (y - y_r)(x_g - x_r)}{(y_g - y_r)(x_r - x_b) + (y_b - y_r)(x_g - x_r)} \cdot \frac{y_b Y}{y Y_b}, \quad (15)$$

In the formula, Y_r, Y_g, and Y_b are the maximum output luminous flux when the input duty cycle of the red, green, and blue light sources is 100%; Y is the output luminous flux of a hybrid light source; (x_r, y_r), (x_g, y_g) and (x_b, y_b) are the color coordinates of red, green and blue, respectively; (x, y) is the color coordinate of the mixed light source.

3.2. Simulation analysis of dimming

Due to the duty cycle is proportional to the luminous flux, and the luminous flux determines the LED luminance. The larger the luminous flux, the brighter the LED luminance. Therefore, the duty cycle is also directly proportional to the luminous brightness of the LED. Calculate and simulate the ratio of different brightness of RGB LEDs controlled by the circuit, change the ratio of brightness of a single LED, and observe the changes in color temperature and color coordinates of the RGB LEDs hybrid light source through simulation. The arrangement of the three types of LEDs is shown in Figure 1, with an observation surface size of 500mm×500mm, with a distance of 100cm from the emitter. In the simulation, the distance remains unchanged, only the brightness ratio of the LED is changed, and the total luminous flux of the set LED is 100lm.

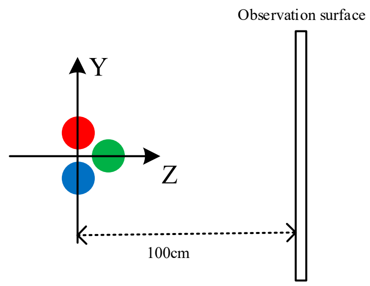

Figure 1. Arrangement of three types of LEDs.

(1) When the control circuit adjusts the luminous flux ratio of RGB LEDs, different color temperatures can be obtained. Simulate the changes in different color temperatures and corresponding color coordinates based on the ratio calculated from equations (15) to (16). As shown in Figure 2, the color coordinate x shows a decreasing trend with the increase of color temperature, while the color coordinate y fluctuates up and down with the increase of color temperature. The fluctuation is greater in the low color temperature stage and smaller in the high color temperature stage.

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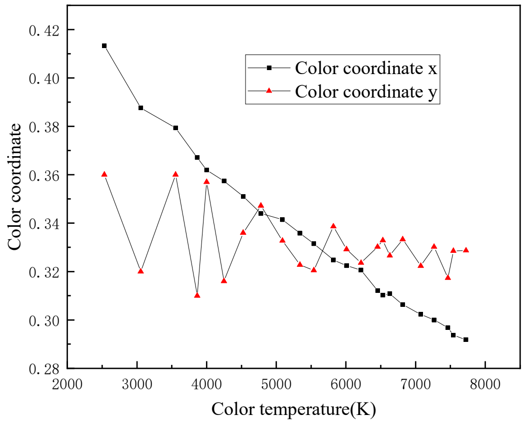
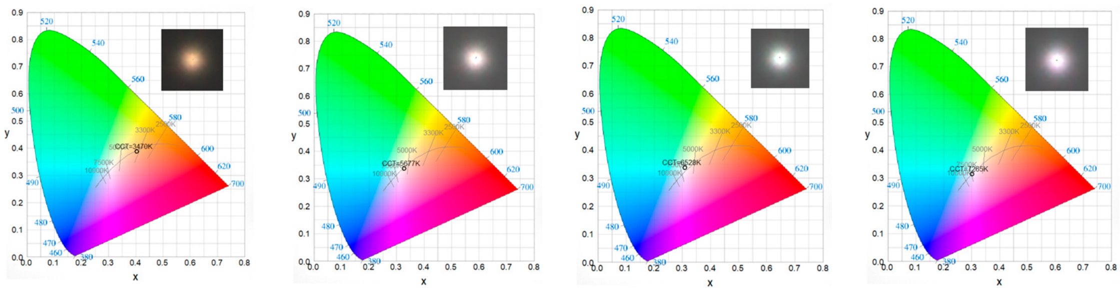


Figure 2. Curve of color coordinates changing with color temperature.

When the duty cycle ratios of RGB LEDs are set to 0.6:0.28:0.12, 0.5:0.32:0.19, 0.47:0.33:0.2 and 0.45:0.34:0.21, the mixed light source on the observation surface is shown in Figure 3. At this time, the color temperature of the mixed light source is 3470K, 5677K, 6528K and 7265K. The color coordinates are (0.4044, 0.3847), (0.3286, 0.3334), (0.3116, 0.3336), (0.3038, 0.3099), and the total amount of light is around 88 lm. From the simulation, it can be seen that the proportion of RGB LEDs has a significant impact on the color coordinates and color temperature of synthesized white light, with a relatively small impact on luminous flux. By changing the duty cycle of red, green, and blue LEDs, the hybrid white light source can change from warm white to cold white.



(**a**) 3470K (**b**) 5677K (**c**) 6528K (**d**) 7265K

Figure 3. Simulating light sources at different color temperatures.

(2) Maintain a constant distance of 100cm between the receiving surface and the light source, and simulate the changes in average light intensity of the receiving surface under different color temperatures. As shown in Figure 4, the average light intensity of the receiving surface under different color temperatures is around 1872lx, with an error of less than 5lx between the maximum and minimum values. When the color temperature is 3500K, 5500K, 6500K, 7300K, it can be seen from the simulated average light intensity distribution of the receiving surface that there is almost no difference. In summary, as the color temperature of the light source changes, the change in the illumination intensity of the receiving surface is very small and can be ignored.

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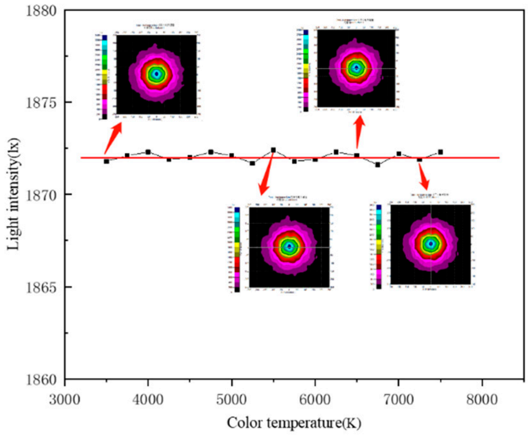

Figure 4. Light intensity distribution under different color temperatures.

(3) Maintain a color temperature of 6500K and simulate the analysis of light intensity on the receiving surface at different distances. As shown in Figure 5, as the distance between the light source and the receiving surface increases, the energy received by the receiving surface becomes less and more dispersed. When the distance between the light source and the observation surface is 50cm, 100cm, 200cm, and 300cm, it can be seen from the simulated light intensity map of the receiving surface that the energy dispersion increases with the increase of distance. In summary, as distance increases, the light intensity on the receiving surface decreases, and distance has a significant impact on the light intensity on the receiving surface.

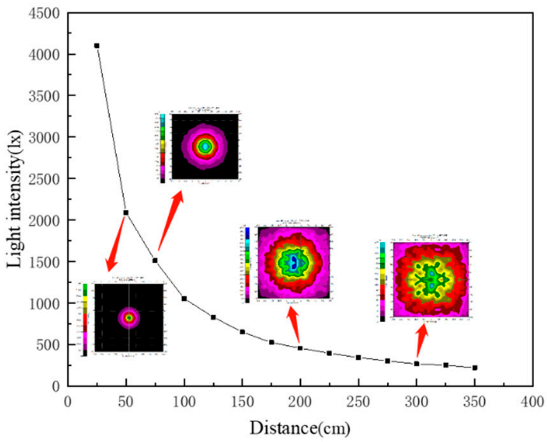

Figure 5. Light intensity distribution at different distances.

3.3. Dimming experiment

This experiment uses hexagonal RGB LEDs beads to form a luminescent light source, and uses the HP350 spectrophotometer produced by Hangzhou Double Color Intelligent Testing Instrument Co., Ltd. to measure the light color parameters. When the three-color LED operates at full current, the light color parameters are shown in Table 1, and the relative spectral power distribution is shown in Figure 6.

Table 1. Three LED Parameters.

LED Type	Chromatic coordinates	Peak wavelength (nm)	FWHM (nm)	Luminous intensity (cd)	luminous flux (lm)
Red LED	(0.6894,0.3099)	630	20	1.8~2.0	67.9
Green LED	(0.1689,0.7232)	520	20	5.0~6.0	178.1
Blue LED	(0.1434,0.0416)	460	20	1.0~1.5	29.0

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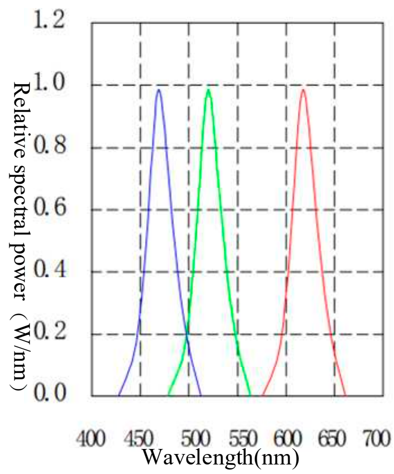

Figure 6. Relative spectral power distribution curves of three types of LEDs.

Adjust the duty cycle of the LED and measure the brightness of the LED. As shown in Figure 7, the variation curve of the measured LED brightness with the duty cycle is shown. The brightness of green light changes significantly with the duty cycle, while the changes in red and blue light are relatively close, with relatively small changes compared to green light.

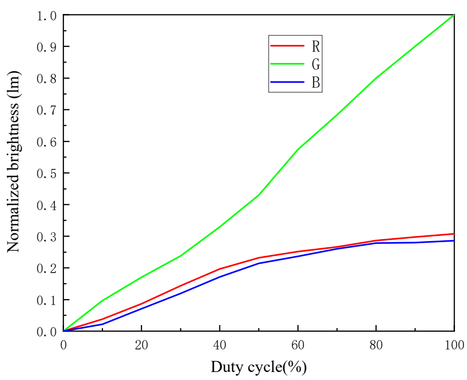

Figure 7. Changes in LED brightness with duty cycle.

The dimming device mainly consists of a switching power supply, control system, driving circuit, and red, green, and blue LED light sources. Figure 8 is a block diagram of the dimming device. The control system sends instructions to the driving circuit to drive a three channel LED, obtaining white light with different color temperatures based on different duty cycles, thereby achieving the effect of LED color temperature adjustment. Figure 9 shows the physical image of the dimming device.

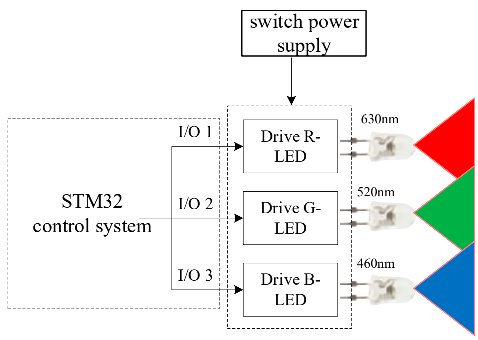

Figure 8. Block diagram of dimming device.

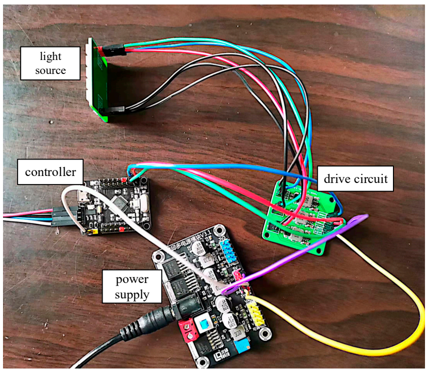

Figure 9. Physical image of dimming device.

RGB LEDs can be mixed according to different proportions to obtain a color temperature range of 2500K~8500K. In order to study the optimal color rendering performance of the light source module during the dimming process, 12 sets of combinations with good color rendering performance were selected in this paper. The mixed light parameters measured using the HP350 spectrophotometer are shown in Table 2. From Table 2, it can be seen that compared with the measured color temperature, the color deviation calculated according to equation (5) is lower than the 50K color temperature limit that can be resolved by the human eye. The average color temperature error is 0.609%, and the difference between the measured and calculated values is small. Therefore, the color temperature adjustment in the experiment is relatively stable.

Table 2. Comparison between measured data and calculated data.

RGB proportion	Measured color temperature(K)	Calculate color temperature(K)	Color temperature difference(K)
0.557:0.301:0.142	2539	2500	39
0.502:0.280:0.218	3030	3000	30
0.476:0.347:0.177	3525	3500	25
0.439:0.304:0.257	4012	4000	12
0.417:0.370:0.213	4532	4500	32
0.405:0.323:0.272	5023	5000	23
0.382:0.361:0.257	5510	5500	10
0.364:0.356:0.281	6032	6000	32
0.347:0.363:0.290	6526	6500	26
0.336:0.355:0.308	7036	7000	36
0.313:0.382:0.305	7540	7500	40
0.302:0.381:0.317	8032	8000	32

The theoretical color coordinates of the synthesized light source are obtained from equations (3) to (4), and the actual color coordinates are measured using a spectrophotometer. Figure 10 shows the variation curve of the measured and calculated color coordinates with color temperature. The error of the calculated excellent coordinate x is less than 0.0007, and the error of the color coordinate y is less than 0.0014. The measured color coordinate is in good agreement with the calculated color coordinate. The color coordinates have a significant impact on low color temperature light sources, while they have a relatively small impact on high color temperature light sources, which is consistent with the simulation results mentioned above.

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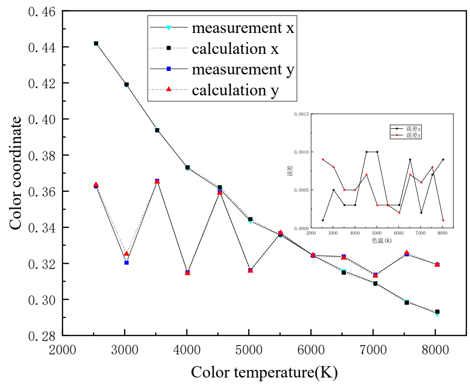

Figure 10. Curve of color coordinates changing with color cemperature.

The duty cycle of RGB LEDs obtained from equations (13) to (15) can obtain mixed white light with different color temperatures. As shown in Figure 11, the duty cycle of red, green, and blue LED varies with color temperature. It can be seen from Figure 11 that as the color temperature increases, the duty cycle of red LED decreases, while the duty cycle of green LED and blue LED increases.

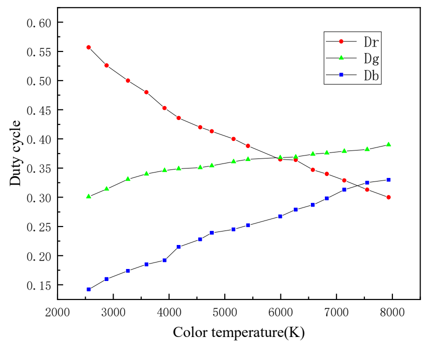

Figure 11. Change of RGB duty cycle with color temperature.

HP350 spectrophotometer is used to measure the luminous flux, irradiance, color tolerance, light intensity and color index of the mixed light source. From Figure 12, it can be seen that the maximum luminous flux set in the experiment is 100lm, and the luminous flux of the mixed light varies between 92lm and 100lm. The resulting luminous flux of the mixed white light is relatively high, and when adjusting the color temperature, the fluctuation of the luminous flux is very small, with a fluctuation of 2.24%. Therefore, the influence of color temperature on the luminous flux is relatively small, which is consistent with the simulation results. The irradiance range of mixed white light is $3.4W/m^2$~$4.2W/m^2$. When the color temperature range is 5000K~6500K, the irradiance reaches the maximum, and the lighting effect is the best. The color tolerance Duv is stable around 0, which is specified to be less than 5.5×10^{-3} can meet the lighting standards [33].

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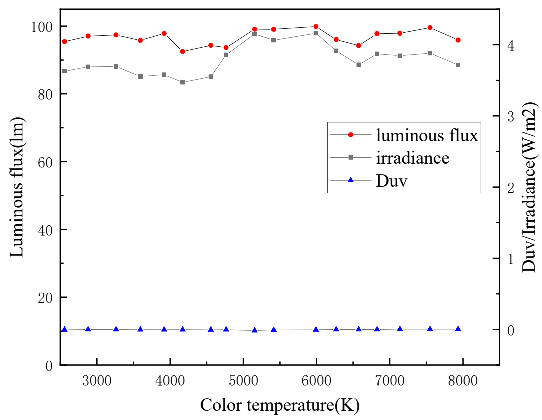

Figure 12. Variation of luminous flux, irradiance and color tolerance with color temperature.

From Figure 13, it can be seen that the illumination value fluctuates less with the change of color temperature, with a difference of only 8.2lx between the maximum and minimum values. The change of color temperature has a small impact on the illumination intensity, which confirms the conclusion of the simulation. In Figure 13, the comparison between the calculated color index and the measured color index according to equations (6)~(7) shows that the theoretical value of the color index is in good agreement with the measured value. The color index is greatly affected by the color temperature. When the color temperature is within the range of 5500K~6500K, the color index is the best. This color temperature range is the light and color temperature at noon. The effect of restoring the color of the object itself is the best, which also conforms to the natural law. The light source with a color index of more than 75 is a high-quality light source [34]. The color index of the mixed white light is more than 76 within the adjustable color temperature range, and the maximum color index is 92, indicating that the experimental mixed white light effect is good.

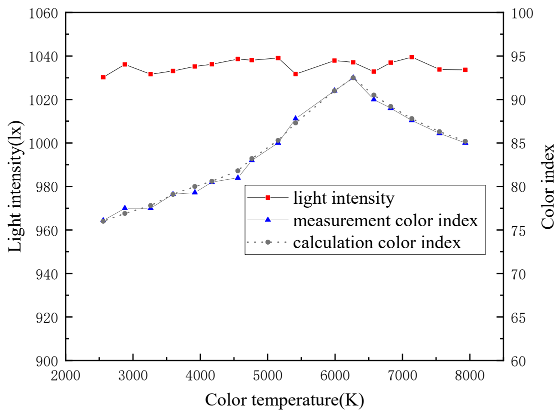

Figure 13. Variation of illuminance and color index with color temperature.

Using the HP350 spectrophotometer to measure the light intensity at different color temperatures and distances, as shown in Figure 14, the curve of light intensity with distance at different color temperatures is shown. The curve of light intensity with distance at each color temperature almost overlaps, indicating that the influence of color temperature on light intensity is not significant. However, as distance increases, the light intensity decreases, indicating that distance has a significant impact on light intensity, verified the conclusions obtained from the simulation.

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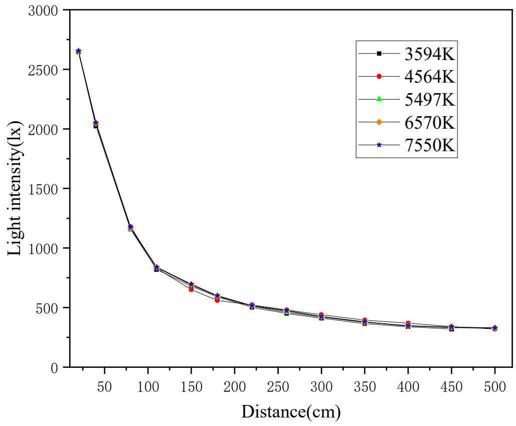


Figure 14. Change of light intensity with distance under different color temperatures.

Maintain a distance of 50cm, as shown in Figure 15, to measure the light intensity at different positions on the receiving surface. The light intensity at direct light is the highest. At the edge of the receiving surface, the light intensity is the smallest, with a maximum illumination value of up to 1500lx. The illuminance value on the receiving surface is uniform at 400lx~1200lx, which meets the requirements of 300lx~1500lx illuminance value formulated by the International Organization for Standardization, with uniformity and lighting effect.

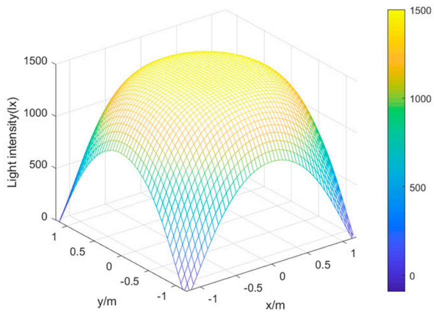
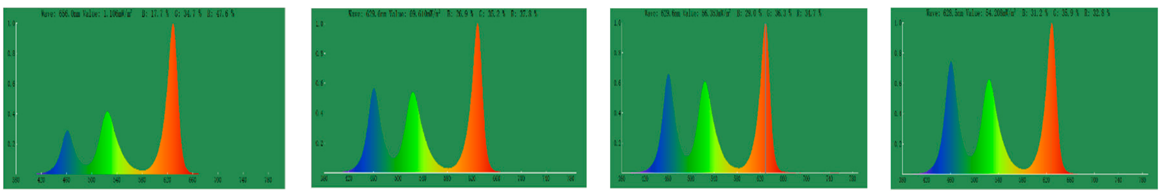


Figure 15. Distribution of light intensity on the receiving surface.

To verify the correctness of the simulation results, the proportions of RGB LEDs were adjusted to 0.6:0.28:0.12, 0.5:0.32:0.19, 0.47:0.33:0.2, and 0.45:0.34:0.21 through the driving circuit, which were consistent with the simulation proportions. The color temperatures of the mixed white light measured using the HP350 spectrophotometer were 3472 K, 5670 K, 6530 K, and 7260 K, which were almost equal to the simulated color temperatures. Figure 16 shows the measured spectrogram, and Figure 17 shows the position information of the mixed white light on the CIE 1931 chromaticity map. At this time, the chromaticity coordinates are (0.4043, 0.3846), (0.285, 0.3333), (0.3117, 0.3335), and (0.3038, 0.3098), which are very close to the simulated chromaticity coordinates, indicating that the mixed white light has a good effect.



(**a**) 3470K (**b**) 5670K (**c**) 6530K (**d**) 7260K

Figure 16. Measured spectrograms at different color temperatures.

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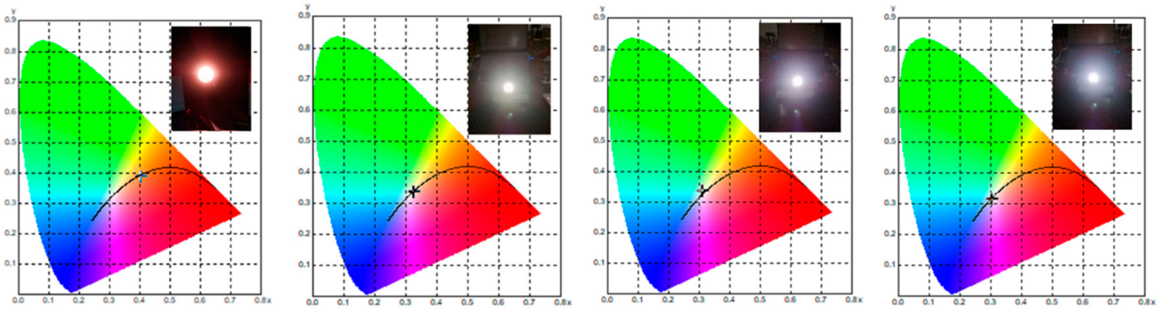

(**a**) 3470K (**b**) 5670K (**c**) 6530K (**d**) 7260K

Figure 17. CIE 1931 chromaticity chart at different color temperatures.

4. Design and Experiment of RGB LEDs Visible Light Communication System

4.1. System working principle and experimental device

The visible light communication system consists of three parts: the sender, indoor channel, and receiver. As shown in Figure 18, the structure diagram of a visible light communication system is shown. The light emitted by three different colored LED chips at the sending end can be regarded as three channels, so color division multiplexing can be used for multiplexing transmission, thereby improving the communication performance of the system. Three channels of PWM are generated by STM32 to drive three kinds of LEDs, and then the three colors are mixed into white light in a certain proportion for output and transmission in the indoor channel. At the receiving end, monochromatic radiation is separated from the white light with corresponding filters to form three channels, and the detector is used to receive signals and display them on the oscilloscope; Then measure the received optical power using an optical power meter and record the data using a computer; Finally, measure the color temperature and light intensity of the mixed white light using a spectrophotometer. The RGB LEDs visible light communication system designed in this article can achieve high-speed data communication through three parallel signals, and use PWM dimming method to output white light to achieve chromaticity control. The experimental setup is shown in Figure 19.

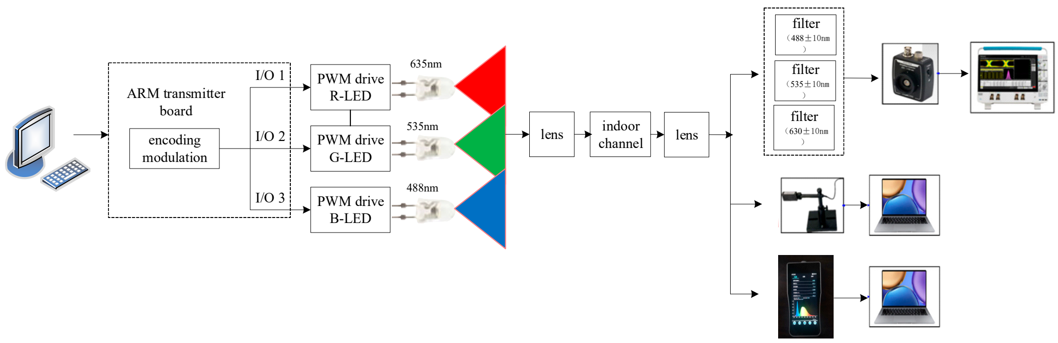

Figure 18. RGB LED visible light communication system.

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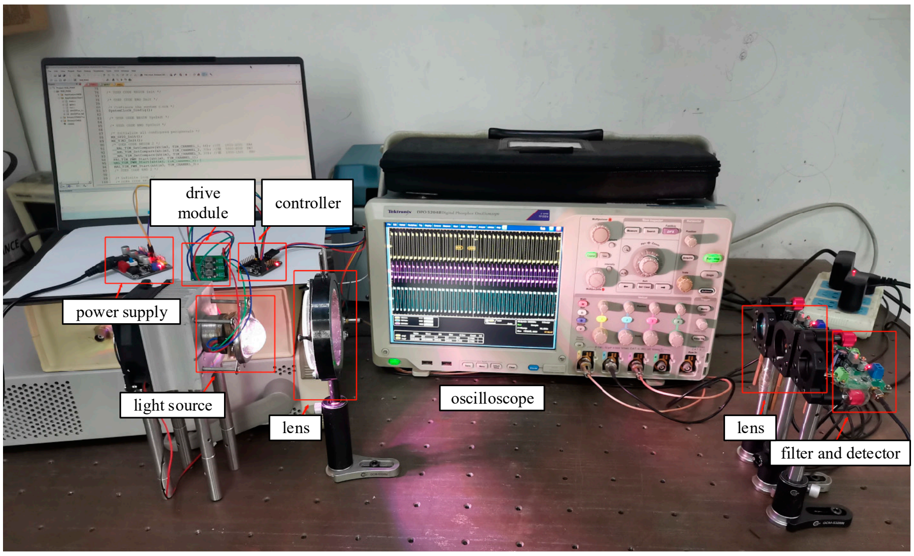

Figure 19. Experimental setup diagram.

4.2. Analysis of experimental results

Due to the integration of lighting and communication in this system, it is necessary to analyze the received light power and light intensity in the visible light communication system separately. The light source is vertically illuminated onto the receiving surface, and the color temperature of the light source is adjusted according to the mixing ratios obtained from the dimming experiment, which are 0.6:0.28:0.12, 0.5:0.32:0.19, 0.47:0.33:0.2, 0.45:0.34:0.21. The OPHIR-PD300-UV optical power meter is used to detect the changes in light power at different distances, as shown in Figure 20. It can be seen from Figure 20 that the optical power decreases with the increase of distance. When the distance is less than 180cm, the optical power decreases rapidly with the increase of distance. When the distance is greater than 180cm, the optical power decreases slowly with the increase of distance. These five groups of curves generally conform to the trend of exponential decay. The receiving surface light power of warm color temperature is relatively small, while the light power of cold color temperature is larger. However, when the distance is greater than 320cm, the light power of the five color temperatures tends to be consistent.

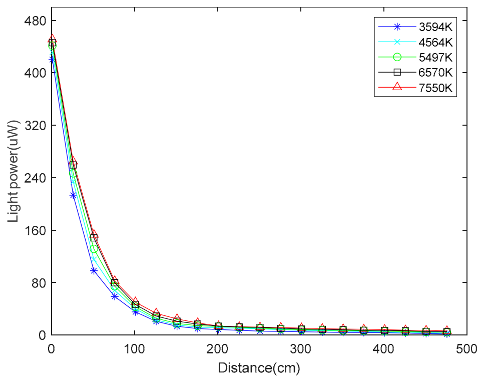

Figure 20. Changes in optical power with distance.

Next, when the distance is 100cm, the distribution of light power on the receiving surface under five color temperatures is measured. Analysis shows that the distribution trend of light power on the receiving surface is consistent among the five color temperatures. Taking a color temperature of 6570K as an example, as shown in Figure 21, the value of light power is the highest at the center position and decreases sequentially around the four positions.

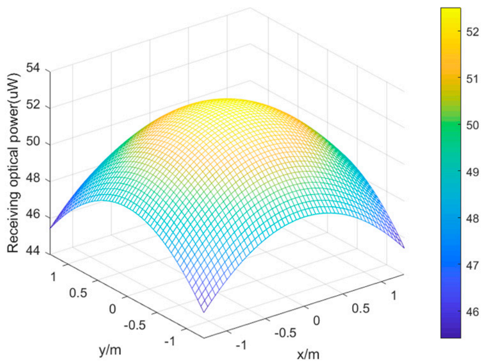

Figure 21. Distribution of optical power on the receiving surface.

Ensure that the distance between the transmitter and receiver remains fixed, change the modulation bandwidth, and calculate the error rate under different modulation bandwidths to obtain the maximum modulation bandwidth for reliable transmission of the system. In the experiment, the communication distance was 250cm, and the modulation bandwidth of the three channels was changed. The total modulation bandwidth under different color temperatures was recorded and synthesized, and the error rate was calculated. As shown in Figure 22, the error rate curve with modulation bandwidth at five color temperatures of 3594K, 4564K, 5497K, 6570K, and 7550K is shown. As shown in Figure 22, as the modulation bandwidth increases, the bit error rate also increases. When the error rate is below 10^{-3}, the maximum modulation bandwidth for the five color temperatures can reach 9.2MHz, 10MHz, 11MHz, 11.5MHz, and 11.7MHz, respectively. The modulation bandwidth for high color temperatures is higher than that for low color temperatures. When the modulation bandwidth is 9MHz, the error rate at all color temperatures is less than 3.8×10^{-3}, achieving reliable transmission of visible light communication systems.

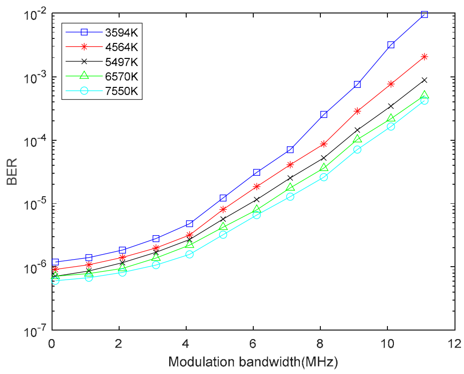

Figure 22. Changes in bit error rate with modulation bandwidth for different color temperatures.

When the modulation bandwidth is 8MHz, as shown in Figure 23, the error rate curve of the five color temperatures of 3594K, 4564K, 5497K, 6570K, and 7550K with distance is shown. As shown in Figure 23, in actual testing, as the distance increases, the error rate of the system also increases, and the speed of change becomes faster and faster. When the transmission distance is 350cm, the error rate at each color temperature is lower than the limit error rate value 3.8×10^{-3} of for forward error correction. The bit error rate of the cold white temperature is significantly lower than that of the warm white temperature. The conclusion is that as the color temperature increases, the communication performance of the system improves. However, when the color temperature exceeds 6500K, the increase in color temperature has a smaller impact on the communication system performance.

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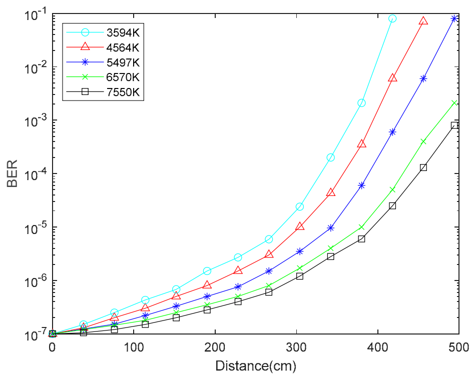

Figure 23. Change of error rate with distance for different color temperatures.

4.3. Discussion

The visible light communication system using RGB LEDs as the light source in this article can conveniently utilize color division multiplexing technology to improve the transmission performance of the entire system. However, the research on RGB multi-color visible light communication system was conducted in the laboratory and has not been used in daily life. Moreover, the three channels system designed in this article has not reached the limit of the number of visible light band channels. In the future, the transmission antenna can be reasonably designed to increase communication bandwidth while mixing multi-color LEDs with white light, making information transmission distance longer and achieving lighting standards in indoor applications, achieving the goal of universal use in daily life.

5. Conclusions

This article studies the chromaticity control of light sources in visible light communication systems. LED white light sources with adjustable color temperatures were obtained through simulation and experiments. When the error rate of each color temperature is below 3.8×10^{-3}, the modulation bandwidth of the system reaches 11.7MHz, the farthest communication distance is 5m, and the illumination intensity is above 400lx. This achieves both communication and lighting functions of visible light, and the following conclusions are obtained:

(1) The light source with different color temperature can be obtained by changing the ratio of red, green and blue LEDs. The general color index of light source with color temperature between 5500K and 6500K is the best. The influence of color temperature on the illumination intensity of the receiving surface at the same distance can be ignored; Distance has a significant impact on the illumination of the receiving surface, as the distance increases. The light intensity rapidly decreases.

(2) The optical power under different color temperatures and distances is measured, and it is found that the color temperature has a small impact on the receiving power value, while the distance has a greater impact. With the increase of distance, the optical power value decreases in the exponential decay trend.

(3) Based on communication experiments under different color temperatures, it was concluded that the communication performance of the system is better in the high color temperature range and significantly better than in the low color temperature range. As the distance increases, the communication error rate under different color temperatures continues to increase.

Author Contributions: Conceptualization, XZ.K.; methodology, XZ.K. and XX.W.; software, XX.W.; validation, JY.L., XX.W. and XZ.K.; formal analysis, XX.W.; writing—original draft preparation, XX.W.; writing—review and editing, XX.W.; visualization, HH.Q.; All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the General Project of National Natural Science Foundation of China, grant number 61377080; the Xi'an Science and Technology Plan, grant number22GXFW0115; the Scientific doi:10.20944/preprints202307.1777.v1

Research Team of Xi'an University, grant number D202309; The Key Industrial Innovation Chain Project of Shaanxi Province, grant number 2017ZDCXL-GY-06-01.

Institutional Review Board Statement: The study did not require ethical approval.

Informed Consent Statement: The study did not require ethical approval.

Data Availability Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare no conflict of interest.

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