



JÖNKÖPING UNIVERSITY
School of Engineering

PERCEIVED BRIGHTNESS OF COLORED LIGHT

**A study about the perceived brightness of near-
monochromatic light in comparison to neutral
white light**

In collaboration with

Volvo Car Corporation

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Abstract

Recently, there has been a notable rise in the use of colored lighting for both indoor and outdoor spaces. This trend necessitates a clear understanding of the principles behind selecting lighting levels that are both ergonomic and energy efficient. The objective of this study was to establish guidelines for planning colored light. An experiment was conducted where the perceived brightness of three different near-monochromatic lights were compared to white light. The stimuli covered a narrow visual field. 33 persons aged 18-40Y participated. Through the measurement of the participants' perception of the amount of colored light required -to achieve the same level of brightness as with white light- the study was able to determine a percentage-based relationship between colored and white light. The result showed that there were clear differences in the perceived brightness of the different colored lights, in line with earlier research with similar conditions. This implicates that the results may be used as a foundation when planning colored light.

Keywords: colored light, perceived brightness, spectral distribution, visual field, white light

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1. Introduction

This study is carried out as the final thesis of the bachelor program in Lighting Design at Jönköping University. It is made in collaboration with the department of Perceived Quality Illumination at Volvo Cars Corporation. The aim of the collaboration is to find general guidelines regarding light levels, that can be applied whenever colored light is included.

1.1 Background and problem definition

There has been a rapid growth in the application of colored light (Olguntürk, 2015). Its primary use is for decorative purposes, such as on facades, parks, tunnels, car interiors, and in a variety of different work environments. It concerns many areas that are under law, regulations, and guidelines, regarding levels of white light and other light-associated parameters (Arbetsmiljöverket, 2022; Swedish Standards Institute, 2014, 2022; Trafikverket, 2022).

Before continuing discussing colored light, it is important to understand that the use of the term '*colored light*' is complex as light does not contain color itself. The perception of color develops in the brain and is partly a result of the reflection of colored surfaces. The color reflected, depends on the spectral distribution of the light – to simplify - it depends on the *color of the light*. How the spectral distribution is perceived depends on the spectral sensitivity of the cone photoreceptors (Boyce, 2014). Colored light consists either of a narrow band of wavelengths, which also can be considered near-monochromatic light, or a mix of various wavelengths (Boyce, 2014; Roufs, 1978; Ware, 2013). Whether light is considered colored or white depends on its coordinates on the CIE Chromaticity curve (Boyce, 2014; Khan et al., 2015).

One of the main reasons behind the increasing popularity behind colored light have is the introduction of LED as the leading light source on the market. Due to its components, it simplifies the manufacturing of colored light sources and thereby makes colored light more accessible (Khan et al., 2015). As colored light has become more prevalent, research has been carried out regarding its effects on humans (Olguntürk, 2015). Many of the studies showed that the spectral distribution of light highly determines its effects. Yang et al. (2018) showed that colored light causes higher levels of discomfort glare than white light, especially blue light with shorter wavelengths. Another study showed that the visual acuity declines with near-monochromatic blue light (Roaf & Sherrington, 1930; Van Buren et al., 2018). The pupil size is also affected by the spectral distribution, which in turn affects the visual acuity as well as the psychological aspect of perceived brightness (Berman et al., 1996; Shlaer et al., 1941; Wardhani et al., 2022). Olguntürk (2015) showed in a study that colored light affects the perception of spaces. This is just a few of the physiological and psychological effects that colored light have on humans. It is clearly important to plan the use of colored light well, especially the choice of levels and spectral distribution.

In order to plan adequate levels of colored light it is of importance to understand the perceived brightness of each color. It is proven that two different colored LEDs with the same intensity can be perceived to have unequal levels of brightness (Aries et al., 2022). For over a century the psychophysical relationship between brightness and luminance of different wavelengths have been studied, resulting in the foundations of photometry (Gibson & Tyndall, 1923). Recent studies have been carried out to

investigate the perceived brightness of colored light in different situations (Caberletti et al., 2010; Hwang et al., 2012; Leube et al., 2018; Olguntürk, 2015).

However, there is a gap between the research field and the current practice field; Many studies within the subject are using other light sources than LED with different spectral distribution (Gibson & Tyndall, 1923; Guild & Inst, 1931; Olguntürk, 2015; Wald, 1945). While some studies examine the perceived brightness of colored light, and how different colored lights affect humans in many aspects, there is no clear definition of specific wavelengths or intensity levels, making the results barely, or not, applicable in the practice field (Berman et al., 1990; Caberletti et al., 2010; Hwang et al., 2012; Olguntürk, 2015). Consequently, lighting designers, among others, uses empirical knowledge to plan light application of colored LED (James Anderson, personal communication, November 9th, 2022; Martin Pålsheden, personal communication, November 3d, 2022). This could lead to overconsumption of energy and negative effects on human well-being (Zhang et al., 2022).

Therefore, this study will use a quantitative approach to establish relationships of the perceived brightness between colored and white light, with the aim that potential findings could lead to basic guidelines regarding the use of colored light and thereby create more ergonomic and energy-efficient solutions (Yang et al., 2018).

1.2 Purpose and research questions

The purpose is to investigate what levels is required of colored light to achieve the same perceived brightness as with neutral white light. The focus is the relationship between white and colored light, and not the exact values.

- What level of near-monochromatic blue light is required compared to neutral white light, to achieve the same perceived brightness?
- What level of near-monochromatic red light is required compared to white neutral light, to achieve the same perceived brightness?
- What level of near-monochromatic green light is required compared to neutral white light, to achieve the same perceived brightness?

1.3 Delimitations

- Neutral white light with a CCT of 4000K will be used as a reference.
- Three different colored LEDs will be used in the experiment; red, green, and blue.
- Near-monochromatic light in this study refers to light with a spectral distribution concentrated within a width of ~75nm and a clear peak.
- Effects on the non-image-forming-system will not be considered.
- The age of the participants is limited to 18-40Y.
- Only participants with normal color vision were included.
- The investigated visual field is <2°.

2 Theoretical framework

2.1 The human visual system

The human visual system is made of an optical system and an image-processing system (Boyce, 2014). To follow, only those parts of the systems that are relevant to this study will be described and assumes a certain knowledge from the reader. For an extended explanation, the book *Human factors in lighting* by P., Boyce (2014) is recommended. As earlier mentioned, the non-image-forming system will not be handled at all.

2.1.1 The retina

The retina is the part that contains cells sensitive to light and as Boyce (2014) states, “the retina is an extension of the brain”. It consists of layers: a layer of retinal ganglion cells of which the axons form the *optic nerve* (see Figure 1); a layer of collector cells that links the photoreceptors to the ganglion cells; and a layer of four types of visual photoreceptors. The four types are grouped into rods and cones. The rods are all the same and contain the photopigment rhodopsin, and therefore also respond to the same spectral sensitivity which makes them unable to detect color (Boyce, 2014). They are sensitive to low light levels which makes them responsible for the night vision (Aries et al., 2022). The cones consist of three different groups with different photopigments which make them sensitive to different wavelengths, and by that, color. Short-wavelength cones (S-cones) are most sensitive to 450nm, medium-wavelength cones (M-cones) to 525nm and long-wavelength cones (L-cones) to 575nm. The distribution of rods and cones over the retina is uneven. What is also to be noted is that the retina is organized in two parts spatially: the fovea, which is the part that detects details, and the periphery, which is the part that indicates in what direction the fovea should be pointed. Although the rods are absent in the center of the fovea, they outnumber the cones in total, with approximately 110 million rods towards 5 million cones (Boyce, 2014). This also means that the rods are responsible for the peripheral vision (Aries et al., 2022).

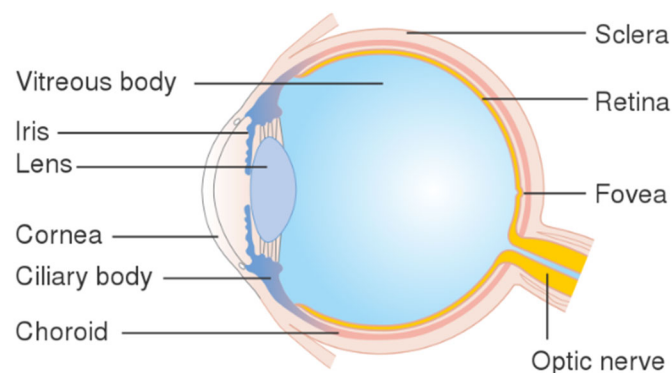


Figure 1. Diagram showing parts of the eye. Note. From Diagram showing the parts of the eye CRUK 326.svg. [Illustration], by Cancer Research UK, 2014, Wikimedia Commons, (https://commons.wikimedia.org/wiki/File:Diagram_showing_the_parts_of_the_eye_CRUK_326.svg) CC Public domain, 2014. Used with permission.

The fovea

In the center of the retina the fovea is located, a small area where mostly the L- and M-cones are concentrated. There are some S-cones in the fovea, but mostly are concentrated just outside the fovea and then the density declines gradually as the eccentricity increases. The center of the fovea is called the foveola (~0,3mm Ø) and completely lacks S-cones. The fovea permits detail resolution, due to various reasons. One being that the network of blood vessels, which almost all the light passes through in order to reach the retina, does not cover the foveola. Also, the ganglion and collector layers are pulled away from the fovea which diminishes the scattering and absorption of light. Another reason is that the shape of the cones which makes them more sensitive to light arriving along the cone axis rather than light arriving at an angle (also known as the Stiles-Crawford effect) and therefore making the fovea less sensitive to scattered light (Boyce, 2014). The distribution of visual photoreceptors over the retina implies that depending on whether a stimulus is in the fovea or the peripheral part of the retina the spectral sensitivity will be altered (Weale, 1953). There is no defined border between the fovea and the surrounding area, and the transition is rather smooth (Strasburger et al., 2011). According to Wandell, the diameter of the fovea is 5,2 deg of arc and the diameter of the foveola is 1° (Wandell, 1995).

The image-processing system

The image-processing system extracts the image that is being produced on the retina and sends it to the visual cortex, located at the back of the cerebral hemispheres. At different stages of the progress, different aspects of the image are being extracted. Notable is that the visual system uses most of its capacity to analyze the information received in the fovea (Boyce, 2014). The image is transmitted from the retina, through the optic nerves which are connected at the optic chiasm where it is being rearranged and further expanded to both lateral geniculate nuclei (LGN). The information is then distributed to the visual cortex where vision occurs (Boyce, 2014).

Visual Stimuli

There are five parameters that describe any visual stimuli: contrast of luminance, retinal illuminance, retinal image quality, difference in color and visual size. In order for the visual system to detect and identify the stimulus these parameters are important (Boyce, 2014). The visual size determinates the image size on the retina (R) and thereby whether it is detected by the fovea or not. In order to calculate the size of the image on the retina, the following parameters need to be specified: The physical size of the stimuli (S), the visual angle (V), the distance from the stimuli (D), and the internal diameter of the human eye (n (=~17mm)), see Figure 22.

$$V = 2 \tan^{-1} S/2D \quad (1)$$

$$R = \tan V \cdot n \quad (2)$$

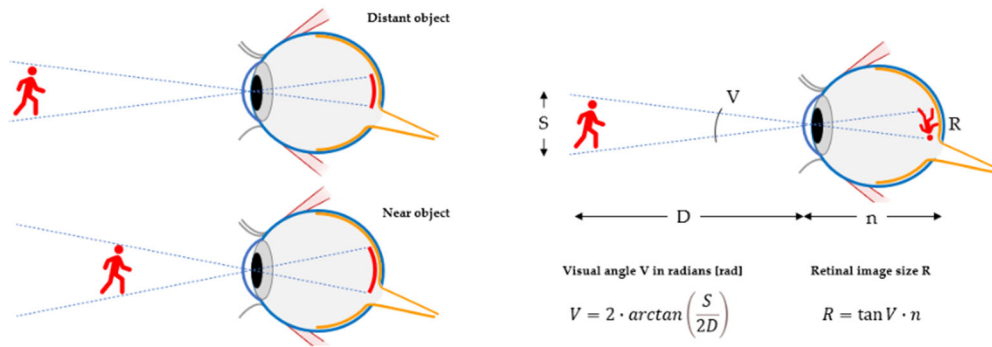


Figure 22. Calculation of retinal image size. Comment. From *Light for health and well-being – Course booklet* (p.24), by M. Aries, et al., 2022, Jönköping University. Copyright 2022 by the copyright holder. Used with permission.

2.1.2 Scotopic, mesopic, photopic

Depending on the retinal illuminance the visual system adjusts its spectral sensitivity. This is since different photoreceptors operate at different light levels. As follows is a summarization of how Boyce (2014) states the three different states of sensitivity:

- Photopic vision: Applies when luminance is above 5 cd/m^2 , where cones are responsible for the retinal response which means that both fine resolution of detail and color vision is possible.
- Scotopic vision: Applies when luminance is below $0,005 \text{ cd/m}^2$, where only rods respond to stimulation. Therefore, color vision is not accessible and detail vision is highly limited as the fovea is blind.
- Mesopic vision: Applies when luminance is between $0,005$ and 5 cd/m^2 . As the luminance declines, the fovea declines in absolute sensitivity, but the spectral sensitivity remains stable until reaching the scotopic state. At the same time in the periphery, the rods are increasingly dominating over the cones. The result is that the color vision in the peripheral part of the retina is gradually being deteriorated and the spectral sensitivity is being shifted to shorter wavelengths.

As a result of the spectral sensitivity being shifted to shorter wavelengths, red objects that in the photopic state would appear brighter than blue objects, will in the mesopic state (reaching the scotopic state) appear darker than the blue object. A phenomenon that is recognized as the Purkinje phenomenon (Hunt & Pointer, 2011). This is due to the rod's spectral sensibility, which lies towards the shorter wavelengths (Shlaer et al., 1941). As previously mentioned, this shift of sensitivity occurs at different pace depending on which area of the retina is being stimulated. If only the peripheral area is stimulated, the shift will occur much slower than if the foveal area is stimulated as well (Roufs, 1978)

2.1.3 Color vision

Human color vision is trichromatic which means that humans with normal color vision can see any color using a combination of the three cones: long, medium, and short regions of the visible spectrum (Boyce, 2014).

Colorblindness is a condition where a person's ability to perceive colors is different due to a deficiency in color vision. This can affect the visual acuity for all or some colors, making it difficult to distinguish between colors, and perceive their brightness or shades. The reason of colorblindness is the absence, or malfunctioning, of one or more of the human eye's cones. Individuals with defective color vision are grouped into three categories (monochromats, dichromats, and anomalous trichromats) based on the number and type of visual photoreceptors and photopigments present in those individuals. Red-green color blindness is the most common form of color deficiency (L-cone related), making it difficult for individuals to distinguish shades of red and green (Aries et al., 2022; Boyce, 2014).

2.2 Photometry

Photometry measures and quantifies the electromagnetic radiation within the spectrum of visible light (380-780nm) weighted against the "relative spectral sensitivity of the human visual system" (Boyce, 2014, p.6) (Behar-Cohen et al., 2011a; Khan et al., 2015).

2.2.1 1924 CIE spectral luminous efficiency function

The spectral sensitivity depends on if the conditions are scotopic or photopic and thereby which state of sensitivity is active (Boyce, 2014). In 1924 the Commission Internationale de l'Eclairage [CIE] started to create an international standard of photometry by defining the 'spectral luminous efficiency', former known as the 'relative visibility function' and also referred to as the $V(\lambda)$ (Schanda et al., 2002). This was based upon work by Gibson and Tyndall (1923), which took data from experiments where the test fields were small ($<2^\circ$ of the visual field) and the amount of light put the visual system in the photopic state. This is also known as the *CIE standard photopic observer*. In 1990, CIE recognized a modified version of the standard photopic observer, which had a higher sensitivity to wavelengths up to 460nm. As it has not been many applications where this is relevant, it has only been considered a compliment to the original standard observer (Boyce, 2014). It was also discussed how the spectral sensitivity changed as the peripheral visual field was used and, and in 1986 CIE approved the *10° photopic photometric observer*. The latter with an even greater sensitivity to short wavelengths as it covers an area of the retina greater than the fovea. By 1951 CIE approved the *standard scotopic observer* (Boyce, 2014). This time the data was taken from experiments made by Wald (1945) and Crawford (1949), with a larger test field (20° of the visual field) and with a luminance of $0,00003 \text{ cd/m}^2$. The main difference is that the sensitivity peaks at 555nm for the modified, 10° , and standard photopic observer, and at 507nm for the scotopic observer, see Figure 33 (Boyce, 2014). This is due to the different light levels and the area of test fields (Schanda et al., 2002).

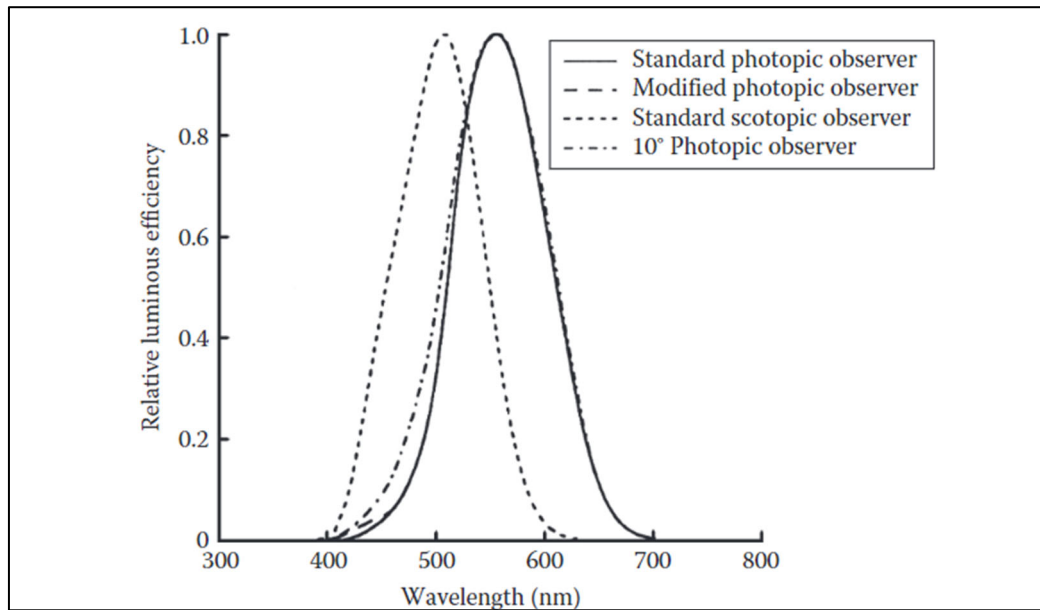


Figure 33. The relative luminous efficiency functions for the CIE standard photopic observer, the CIE modified photopic observer, the CIE standard scotopic observer and the CIE 10° photopic photometric observer. From *Human Factors in Light Third Edition* (p.6), by Boyce P, 2014, Taylor & Francis Group. Copyright 2014 by Taylor & Francis Group. Used with permission.

CIE have later on developed a system for mesopic light conditions which is adjustable according to the light levels. This could be of great use when planning outdoor lighting, which often neither fit into the photopic nor the scotopic range (Boyce, 2014).

Critique regarding the Luminous efficiency function

There is research showing that the data on which the basics of photometry is founded on, is inconsistent as well as insufficient (Padgham, 1971; Roufs, 1978; Schanda et al., 2002). Padgham states that even though photometry “works reasonably well in practice” (s.578), (where the color saturation of the light typically is low), this especially concerns highly saturated colored light (s.578, 1971).

2.3 Colorimetry

Colorimetry is the science of color measurement based on the functions of the human eye, and how the brain receives and interprets different colors. In the human eye, color perception is influenced by the properties of three cone photoreceptors and their different spectral sensitivity. Colorimetry also aims to give numerical specification and measurement of color (Stockman, 2003). CIE colorimetry system and other studies identified a way of measuring the human eye’s sensitivities to different wavelengths. These studies are based on observers matching of two colors. They noticed that color appearance is affected by field size. Increasing the field size from 2° to 10° results in a greater sensitivity of the visual system to the portion of the visible spectrum below 550 nm (Boyce, 2014). Understanding the spectral sensitivities of the different types of cone photoreceptors in the human eye, is essential for accurately modeling human color vision, as well as for practical applications such as color matching and specification

(Stockman, 2019). Earlier research within the field used direct observations to compare and evaluate colored light with different luminance. As the photometric quantity of luminance was used as a reference value, the results rather showed the discrepancy between the perceived brightness and the established luminous efficiency function (Padgham, 1971).

2.3.1 CIE Chromaticity curve

As colorimetry aims to quantify the human color perception it recommends different methods to do so. One of the methods is the CIE chromaticity curve (Khan et al., 2015), see Figure 44. It is based upon a mathematical construction where different colors are assigned different coordinates (x , y). It establishes that all spectral distributions that humans perceive as the same color will have the same coordinates at the curve, and vice versa, that when it is perceived as different colors, it will be located at different positions (Boyce, 2014). Further on by Boyce it is stated that the CIE chromaticity curve consist of four important components:

- The spectrum locus: This is the outer curved boundary. Colors that consist of single wavelengths are positioned on this curve.
- The purple boundary: Is the straight line between the ending points of the spectrum locus. This is the locus where the most saturated purples are positioned.
- The equal energy point: The colorless surface in the middle of the diagram.
- The Planckian locus: This curve runs through the same coordinates as objects that works in the same way as a black body. To quote Boyce (2014): “that is, the spectral power distribution of the light source is determined solely by its temperature.” (p.14).

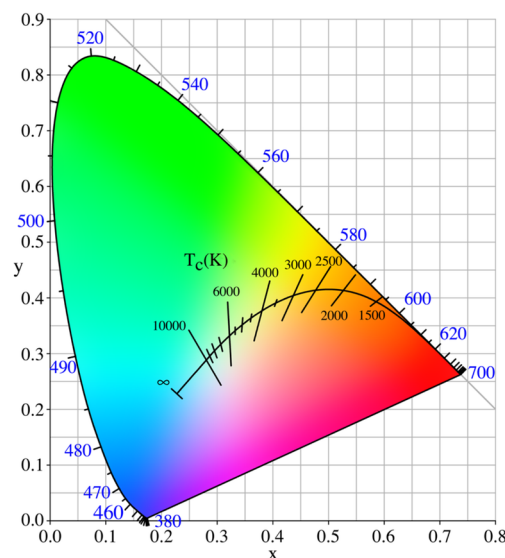


Figure 44. The CIE Chromaticity Curve. From PlanckianLocus.png, en:User:PAR, 2005, Wikimedia Commons, <https://commons.wikimedia.org/wiki/File:PlanckianLocus.png>. CC Public domain, 2012. Used with permission.

2.4 LED-technology

The spectral distribution of a LED is depending on the materials used in the semiconductor. The luminance flux is determined by the temperature of the semiconductor and the current through it. In order to create white light, there are different methods: either to combine three (or more) LEDs, or, to combine a LED emitting visible radiation in the short- or long-wavelength spectrum with a layer of phosphor (Khan et al., 2015). The spectral distribution depends on the components and the technique, but it is rather the latter that determines its general outcome (Boyce, 2014).

2.4.1 Color temperature (CCT)

Correlated color temperature (CCT) is used to define different kind of white light by comparing the color appearance of the light source with the Planckian locus. The temperatures are usually given in unit Kelvin (K). By using exact chromaticity coordinates it is possible to get a specific and clear image about the output of the light source (Boyce, 2014).

To simplify, the industry uses three classifications to define color appearance of white light: warm white (WW), neutral white (NW) and cool white (CW). These three groups cover different sections of Planckian locus, according to Khan et al., (2015);

- WW: $CCT < 3500\text{ K}$
- NW: $3500\text{ K} \leq CCT < 5000\text{ K}$
- CW: $CCT \geq 5000\text{ K}$

This is further supported by a study about white lighting where Rea and Freyssinier (2013) defines that high CCTs are above 4000K and that low CCTs are below 4000K. Notable is that low CCTs “are associated with chromaticities that lie well below the black body locus” (p.82).

Duv is used to further define white light, which is a metric that specifies the distance between chromaticity coordinates of a light source and the nearest point on a Planckian locus. Light sources can be considered white if their Duv values are no greater than ± 0.006 . In order to determine the color appearance of a light source, two important variables must be considered: Correlated Color Temperature (CCT) and Duv (Boyce, 2014).

2.4.2 RGB technology

A RGB LED, or Red-Green-Blue Light Emitting Diode, emits light in multiple colors by combining different intensities of red, green, and blue light. This LED product consists of three separate LED chips and has a spectrum with different wavelengths. Several colors can be produced by adjusting the brightness of each color (Ware, 2013). Monochromatic light is a visible radiation with only one type of wavelength (Oxford Reference, 2023). While near-monochromatic “[...] is used to refer to a spectrum consisting predominantly of a single harmonic which will have a bandwidth on the order of the laser bandwidth.” (Yeung et al., 2013, s.3). The chromaticity coordinates of all near-monochromatic lights are located on the spectrum locus (Ware, 2013).

2.5 Psychophysics

One of the fundamental disciplines in the study of the human brain and the visual capabilities is visual psychophysics, and it is the core methodology in vision research. (Lu & Doshier, 2013). As G. Gescheider describes it in the book *Psychophysics: the fundamentals*, what was former known as a philosophical field, transformed into a scientific discipline as the physicist G. T. Fechner (1997) started to apply techniques to measure mental events. The author further concludes that psychophysics mainly investigates the connection between “sensations in the psychological domain and stimuli in the physical domain” (Gescheider, 1997, p.1). A central concept in psychophysics is the sensory threshold. It concludes that in order to experience a stimulus consciously it has to exceed a certain amount (Falmagne, 1985). One application of this is to measure the limits of the sense organs of the human, and further conclude the *absolute stimulus threshold*; “the smallest amount of stimulus energy necessary to produce a sensation” (Gescheider, 1997, p.1). In order to define the amount of stimulus necessary for a person to notice a change, the term *difference threshold*, or *just noticeable difference (JND)* is used (American Psychological Association, n.d.; Falmagne, 1985). Absolute and difference thresholds can be changed by varying different parameters of the stimulus and the relations are called *stimulus critical value function*. They describe how the aspect of the stimulus changes the threshold (critical stimulus value) as a function. Examples of aspects of a stimulus are intensity level, wavelength, adaptation time, etc. (Gescheider, 1997).

In the field of lighting the most common psychophysical concept is the relationship between the psychological response of brightness, and luminance, a physical stimulus (Ngai, 2000).

2.5.1 Brightness and luminance

The connection between brightness and luminance follows a power law, that is not linear, and is as follows:

$$B = kL^n \quad (3)$$

Where B is the magnitude of the brightness, k is a constant, L is the stimulus luminance (cd/m^2) and n is an exponent. The value of the exponent has been found to be influenced by various parameters, among them counts the luminance and size of the field surrounding the target (in relation to the target), the observer’s visual system’s grade of adaptation, and colors (Boyce, 2014).

2.5.2 Brightness

The term “brightness” has been used in a wide range of contexts and the following paragraph aims to clarify some and specify the use of it in this study.

In a review made by Behar-Cohen et. al., where explaining radiometry, it was mentioned that “Radiance is used to describe the “brightness” of a source (Behar-Cohen et al., 2011). The citation-marks indicates that the word is not established within the radiometric quantities and rather intends to explain the physical quantity with a sensory stimulus. What is notable is that the United States Federal Trade Commission [FTC] have used the word brightness on the Lighting Facts label (that is mandatory on all packages of light sources since 2012), where it stipulates the amount of lumen the light source emits, which corresponds to the photometric quantity of luminous flux. Further

on their webpage, it is written that “Lumens measure brightness” (FTC Consumer Advice, 2021). This take on brightness as a photometric quantity is traceable, not yet logic, to the fact that luminance was formerly referred to as brightness (Behar-Cohen et al., 2011). There is a clear link though, to Boyce (2014), that explains that brightness is the light that is seen to be emitted from a source as well as Ware that writes “The term *brightness* usually refers to the perceived amount of light coming from self-luminous sources.” (Ware, 2021, P.82). He further states that “Perceived brightness is a very nonlinear function of the amount of light emitted by a lamp.” (p.82). The last quote affirming the earlier mentioned power law. As a last contribution to the clarifying of the word, the International Union of Pure and Applied Chemistry [IUPAC] writes that brightness is an “Obsolete term. This term is reserved for non-quantitative reference to physiological perception of light [...]”(Gold, 2019, p. 310). In conclusion, in this study *perceived brightness* will be used and refers to the *psychological* response to the perception of light.

2.5.3 Perceived brightness

Research showed that white light sources with the same luminance and various color temperatures (CCT) were perceived differently; the white light with higher CCT was perceived brighter than white light with lower CCT. Further studies showed that perception of brightness for white lights with the same CCT differed due to the light spectral distribution (Boyce, 2014).

Lately many studies showed that colored light influences visual acuity and perception of brightness (Hwang et al., 2012). Monochromatic blue light has been shown to reduce the visual acuity (Leube et al., 2018; Pokorny et al., 1968). Colored light with different spectral content affect the cognition of brightness differently. When comparing two different colored lights with the same luminance, the one with higher color saturation was perceived brighter. For example, green, red, and blue lights were perceived brighter than yellow, due to that they were more saturated (Boyce, 2014).

More studies about colored light and perceived brightness showed that lights with wavelengths between 550 and 560 nm (yellow-green), appear brighter than lights with wavelengths on the extremes of the visible light spectrum, which is related to the spectral sensitivity of human vision (Bornstein, 1975). Blue light is perceived brighter, compared to red and orange light on a wider visual field (135°) (Caberletti et al., 2010). Cyan LED light have relative similar brightness compared to white LED light. Green light is perceived brighter than other colored light, especially red light (Hwang et al., 2012).

2.5.4 Pupil size

The size of the pupil depends on various factors. The two most important being the distance to an object on which the vision focuses, and the amount of light reaching the inner layer of the eye, called retina. The age of the eye and certain emotions also affect the size of the pupil (Boyce, 2014). As mentioned before, there is a direct relationship between the spectrum of light and perceived brightness. According to studies made by Berman, S., et al. (1993) it is shown that the rods affect pupil size, which in turn affects the perceived brightness. Light sources with a high concentration of short wavelengths, produce smaller pupil sizes than light sources with a low concentration of short wavelengths. As a result of a smaller size of the pupil, the quality of retinal image is

much better (Boyce, 2014). There is a tendency to overestimate the brightness of a stimulus when our pupils are small and vice versa. In contrast, when our pupils are large, the opposite occurs (Wardhani et al., 2022). Sulutvedet et. al., (2021) explained that the retinal adaptation to different pupil size affects brightness perception; a large pupil may result in a retinal adaptation to the decreased brightness perception. The effect of pupil size on perceived brightness doesn't appear in normal daily activities (Boyce, 2014; Wardhani et al., 2022).

2.6 Research question linked to theoretical field:

In order to perform the experiment and analyze the results, research within respective fields were necessary. The following graph shows what fields have been studied. See Figure 55.

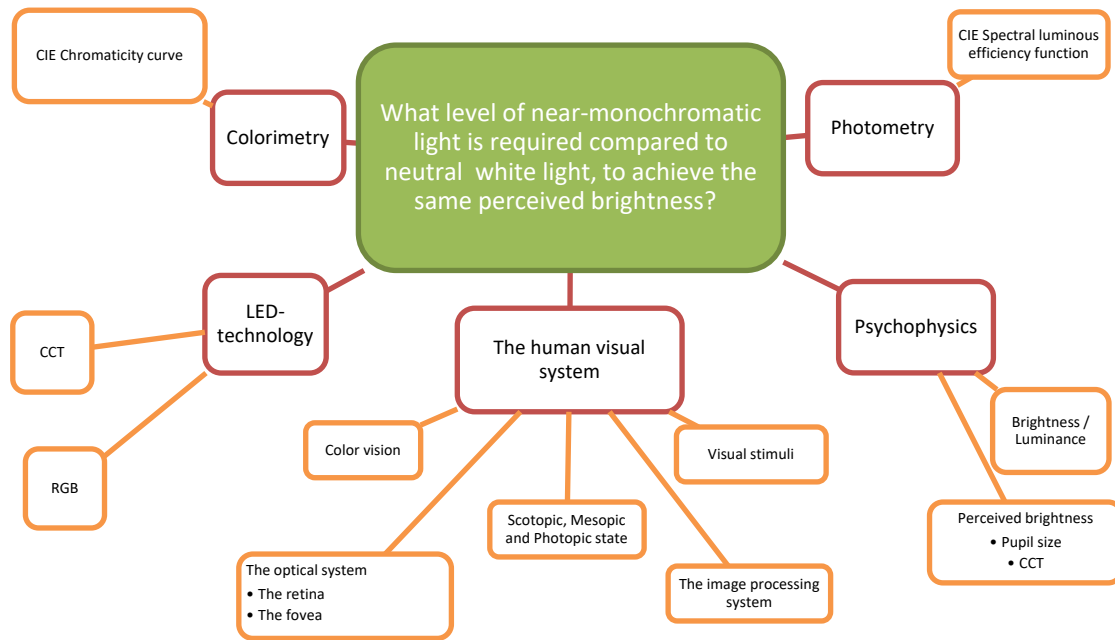


Figure 55. Research questions linked to theoretical field

3 Method and procedure

3.1 Research strategy

The research strategy in this study was quantitative. This since the collected data was numeric, and at a ratio scale, which made it suitable for a quantitative study (Bryman, 2018). The study was also suitable for a quantitative approach because statistics was used to process the collected data. The study was performed as an experiment where good laboratory practice was exercised (Säfsten & Gustavsson, 2019).

3.1.1 Research question linked to choice of method

The choice of the method of experiment was based upon on of the aims of the study; to strengthen existing theories and thereby contribute to the explanation of them (Montgomery, 2013). As the question regards psychological sensations (perceived brightness) as well as physical stimuli (illuminance) an experiment with the classical psychophysical method; *method of limits*, were used (Gescheider, 1997). The psychophysical criterion in this experiment was the visual acuity of Landolt C-rings, in line with former experiment with similar aims (Ives, 1912; Roufs, 1978)

3.1.2 Data collection strategy

As the primary data was numeric, Gustavsson and Säfsten (2019) recommend measurement as a data collection strategy. It was collected by measurement of the intensity levels and Lux, needed for the participants to perform a certain visual acuity test. The numeric values of the measurements themselves were not of significance as the aim was to find the relationship / ratio between the different variables. All data values were at a ratio scale as both intensity levels and Lux have a natural zero point (Gustavsson & Säfsten, 2019).

3.2 Outline of experiment

3.2.1 Participants

The participants were selected by a convenience sampling with the following inclusion criterias: Minimum 20 participants in the age range of 18 to 40Y with fully functional color vision. This in order to avoid deviations from the *CIE standard photopic observer* (Roufs, 1978). The gender-division among the participants was intended to be as close to 50%F-50%M as possible. The participants were students and employees at Jönköping University, Sweden, during spring 2023. They were informed through internal electronic correspondence and further personally invited at the day of the experiment. A compensation in form of a 75g chocolate bar was given to all participants.

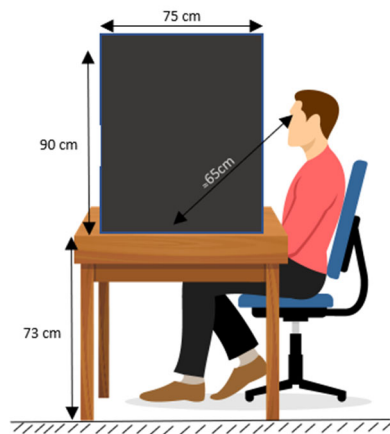
Data was collected from 33 participants, 16 females and 17 males. All the participants' color vision was controlled by an Ishihara color-blindness test (Ishihara, 1979) (see Appendix 1). The age range of the participants were 20-40Y with a mean age of 26,6Y and a median age of 25Y. 8 out of 33 participants used visual aid during the experiment. Out of 33 participants, 21 hade a background in Lighting Studies, see Appendix 2.

3.2.2 Experiment (room)

The experiment room was divided into three parts by black fabric, all with the same area: 5 x 2,5m. The first room that the participants entered was the information room where they would get information about the procedure of the experiment, perform a color-blindness test, and sign the consent. In the room there was a desk with an office chair. On the desk the Ishihara color-blindness test and the consent-papers (see Appendix 3) were placed. The only source of light in the room was a desk lamp with a tungsten halogen light source, of 2700K and with a Ra of >99, that would give the estimated illuminance on the desk was 542 lux. The second room was the test-room where the experiment would be performed. In the room there was a desk with an office chair with adjustable height. On top of the desk the apparatus was placed. The only source of light in the room was a desk lamp on top of the desk which was turned off during the experiment. Behind the information- and test room the control room was located. Only the researchers of this study had access to this room. For a detailed description of the whole setup, see Appendix 4.

3.2.3 Apparatus

According to the study made by Hwang et al. (2011) where the optimal illuminance of colored LED was investigated, the outlines of the apparatus were based on their method. The apparatus used in the current study had a size of; length and width: 75cm, and



height: 90cm. At the front of the apparatus a window was located. The size of the window was; width: 68cm and height 12cm. The window was centered in the x-axis and the bottom of the window where placed 35cm from the bottom of the apparatus. The apparatus was placed on a table with a height of 73cm resulting in the bottom of the window being placed at 108cm above the floor. The apparatus inside and outside was covered in black cotton fabric. In order to let the participants comfortably place themselves with their eyes in the center of the window, an office chair with adjustable height were placed in front of the apparatus, see Figure 66.

Figure 66. The apparatus

In the ceiling of the apparatus a 5V RGBW-LED-strip were mounted. The LED-strip had 4 chips in every LED (RGBW) and with a wide viewing angle at 120° (see Appendix 5). It contained 144 LED/m which on 5.6 cm gave 8 LEDs. The LED-strip were connected to a control unit which was located outside the apparatus and maneuvered from the information room. The control unit were a RGBW-mixer with a touchscreen. There were five different parameters that could be controlled: R, G, B, W, and total intensity, all in the range of 0-255. The maximum intensity levels of every chip with their respectively Lux-value (measured 90cm directly underneath the LED-strip) are presented in Table 1. The white light had a CCT of 4000K and Duv of -0.0007, also known as neutral white (Rea & Freyssinier, 2013). The spectral power distribution (SPD) of the different LED-chips was measured with a spectrometer of the brand Asensetek, model Lighting Passport, ALP-01. The SPDs are presented in Figure 77.

The LED-strip was mounted at the center of the ceiling of the apparatus parallel to the window, aimed towards the floor of the apparatus in a 90° angle.

Table 1. Specifications of R, G, B and W

	White light	Red light	Green light	Blue light
Max intensity	255	255	255	255
Max illuminance	20 Lux	2,6 Lux	7,7 Lux	3,3 Lux
λ_p	-	634 nm	519 nm	464 nm

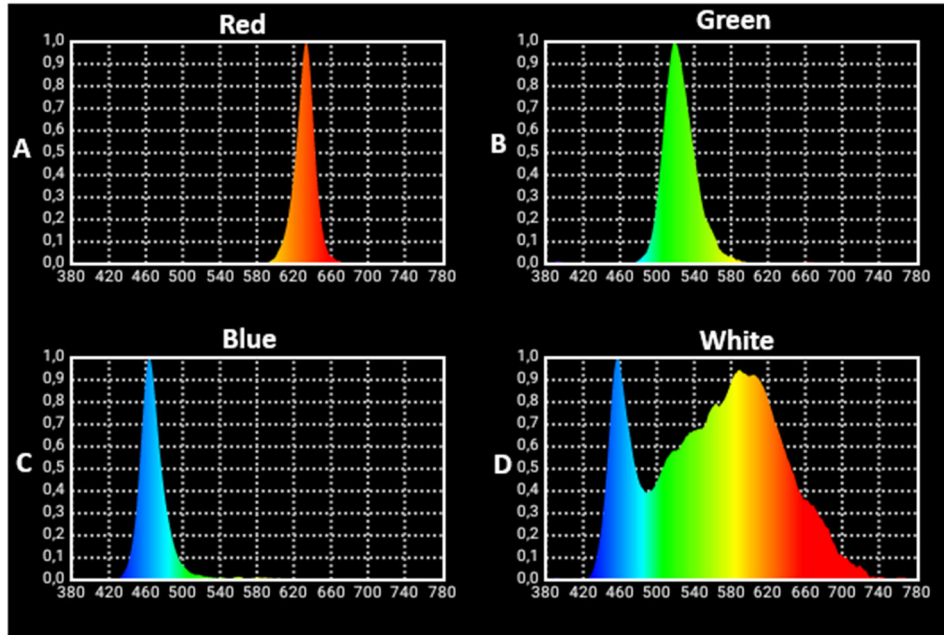


Figure 77. SPD for the four LED-chips

Directly underneath the LED-strip, on the floor, a visual acuity test of type Landolt C was placed, see Appendix 6. There were four rows of C-rings, all in the same size, and with the opening of each ring directed in one out of four possible directions (up, down, left, and right). The distance from the eye of the observer to the Landolt C test was ~65cm. The size of the test was 7,5x21cm and the Landolt C rings had a Ø of 0,4cm and an opening of 0.01cm. The image size of Landolt C ring on the retina was $R \sim 0.105$ mm, and the visual angle of Landolt C ring was $V \sim 0.352^\circ$ (according to equations 1 and 2, $S \sim 0.4$ cm, $D \sim 65$ cm, $n \sim 17$ mm).

Next to the Landolt-C test an external sensor of a Lux-meter of the brand Hagner (model EC1, Inst. No: 7832) was placed. The sensor was connected to the Lux-meter that was placed in the control room.

3.2.4 Data collection

The data was collected in an excel sheet were the demographic information together with the participants individual codes where listed. Data regarding (R, G, B, and W) intensity levels and amount of Lux necessary for the participants to read the visual acuity test where collected.

3.2.5 Procedure

The participants were first shown into the information room, one by one. There they received information about the of the study and their color vision were controlled. After completing an Ishihara color blindness test (see Appendix 1) and signing the consent the participant was shown into the test room. In the test room the participant were placed so that the chin was aligned with the bottom of the window of the apparatus.

In order to allow the eyes to adapt, the first 30 second were spent in darkness while the demographic information about the participant were collected orally. After that the white light was dimmed up in a regular pace of 1 level/sec by one of the researchers, located in the information room. The participant then used the word ‘stop’ whenever she or he felt that he could read the Landolt C-test in a ‘relaxed and comfortable way’. The participant was then asked to read the test, and if they had more than 50% correct answers, the dim-level were passed to the researcher in the control room who also noted the Lux-value. The threshold of percentage of correct answers is, according to Boyce, “a matter of convention” (2014, p.64). If they had less than 50% correct answers on the test, the light would be adjusted until they had. After that, 30 sec of darkness followed, and then the procedure was repeated with red, green, and blue light. The order of the RGB-lights was randomized using an online randomizer. For a detailed timeline of the procedure, see Figure 8.8. The data collected was then summarized in an excel sheet where further statistical analyzes proceeded.

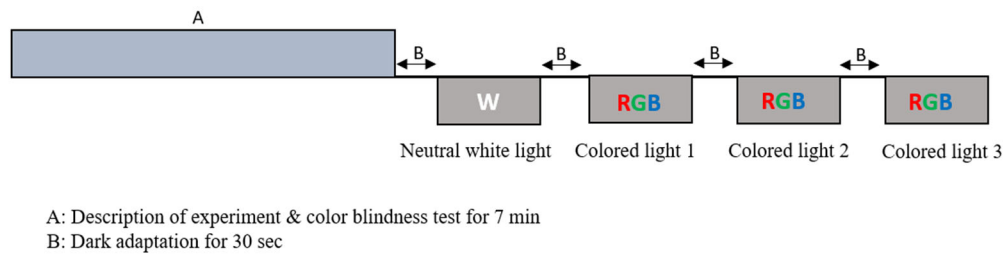


Figure 8.8 Timeline for the experiment

3.3 Analyze method

The data collected was analyzed by descriptive statistic, univariate, and bivariate analysis (Gustavsson & Säfsten, 2019). The measured levels of Lux and intensity was compared in order to establish the correlation coefficient between each one of them (Nyquist, 2021). The demographic data was summarized by descriptive statistic. The result from the measurments were first analyzed by descriptive statistic, then univariate analysis and then further on by bivariate analysis from which statistical inference were made. Last the levels of the colored lights were compared with the levels of the neutral white light.

4 Results

In this section the results of the required illuminance levels of colored light, to achieve the same perceived brightness as with neutral white light, will be presented by color. In order to compare the results, both intensity and illuminance have been converted to percent. The maximum intensity level (100%) of each color is based on the value of 255 as the dim-levels range from 0 to 255. The maximum illuminance level reached at dim level 255 is presented per color. Each part starts with a descriptive statistic of the illuminance levels followed by a presentation of the correlation between illuminance and intensity. Subsequently, a t-test comparing the red, blue, and green light to the white light will be performed, and finally a graphic comparison between the illuminance levels of white and each color will be presented. Alpha level is set to 0.05. At the end of the section, descriptive statistic of the demographic data will be shown to provide a basis for further analysis of possible dependent variables.

4.1.1 White

The maximum illuminance level (100%) of white light was measured to 20 lux. The mean illuminance level was 6.8% ($N = 33$, *Median* = 4.5%, *SD* = 5.5%, range: 1-22%), see Appendix 7. The results distributed by illuminance levels in percent are presented in the following histogram, see Figure 99.

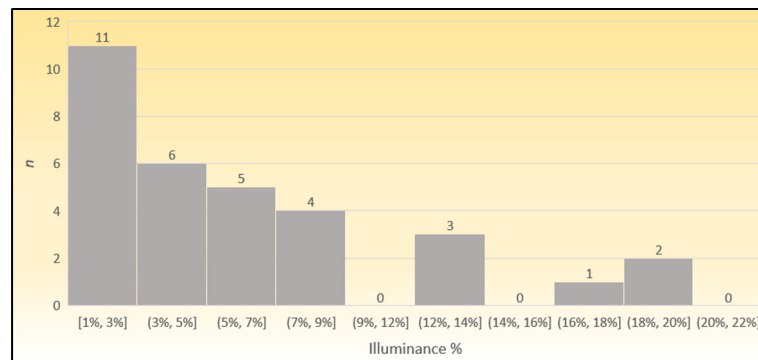


Figure 99. The results for white light, distributed by illuminance levels in percent.

The Person's Correlation Coefficient is set to $r(31) = .9963$, $p = < .00001$. This concludes that the result is significant and as shown in the graph (Figure 1010) there is a strong positive correlation between the measured illuminance and intensity levels of white light.

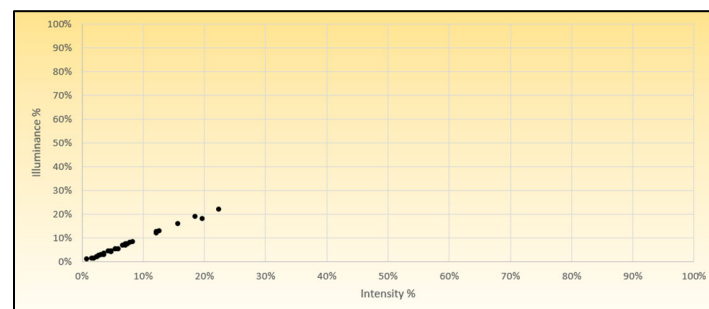


Figure 1010. Correlation between illuminance and intensity in percent, of white light.

4.1.2 Red

The maximum illuminance level (100%) of red light was measured to 2.6 lux. The mean illuminance level was 15.3% ($N = 33$, $Median = 7.7\%$, $SD = 15.8\%$, range: 3.8-76.9%), see Appendix 8. The results distributed by illuminance levels in percent are presented in the following histogram, see Figure 1111.

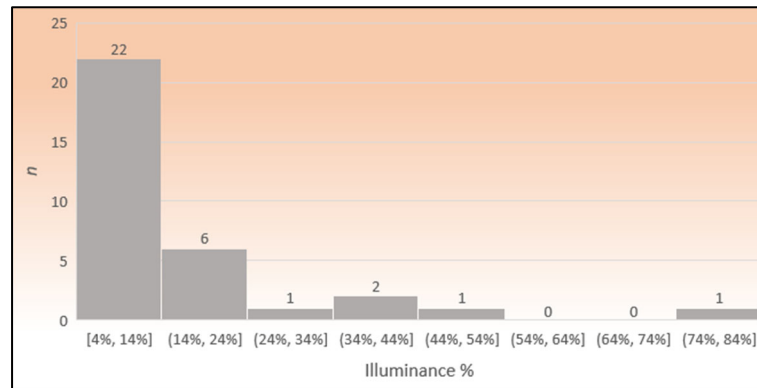


Figure 1111. The results for red light, distributed by illuminance levels in percent.

The Person's Correlation Coefficient is set to $r(31) = .9967$, $p = < .00001$. This concludes that the result is significant and as shown in the graph (Figure 1212) there is a strong positive correlation between the measured illuminance and intensity levels of red light.

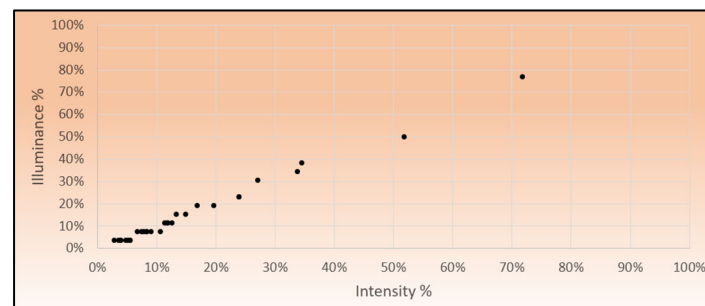


Figure 1212. Correlation between illuminance and intensity in percent, of red light.

A two-tailed t-test revealed a significant difference between the illuminance levels of white light compared to the illuminance levels of red light ($t(32) = -3.9186$, $p < .001$), see Appendix 11.

The mean for the illuminance levels of white light ($M = 6.8\%$, $Variance = 0.3\%$) was significantly lower than the mean for the illuminance levels of red light ($M = 15.3\%$, $Variance = 2.5\%$).

To summarize the statistics of the red light, the graph that follows shows the mean of the illuminance levels of red light compared to the mean of the illuminance levels of white light (see Figure 1313). Both percentages are calculated according to each color's individual maximum illuminance levels.

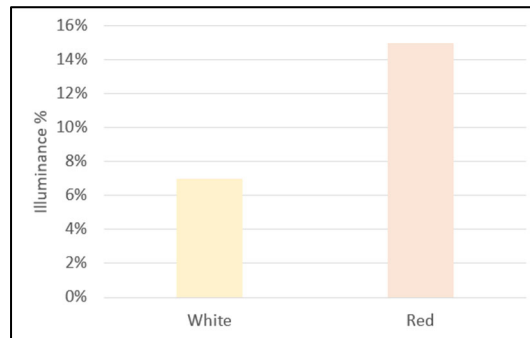


Figure 1313. Mean of illuminance levels in percentage of white and red light. Note that the Y-axis shows the percentage of each colors individual total. 100% illuminance of white is set to 20 lux and 100% of red is set to 2.6 lux.

4.1.3 Green

The maximum illuminance level (100%) of green light was measured to 7.7 lux. The mean illuminance level was 7.8% ($N = 33$, Median = 5.2%, $SD = 7.9\%$, range: 1.3-41.6%), see Appendix 9. The results distributed by illuminance levels in percent are presented in the following histogram, see Figure 1414.

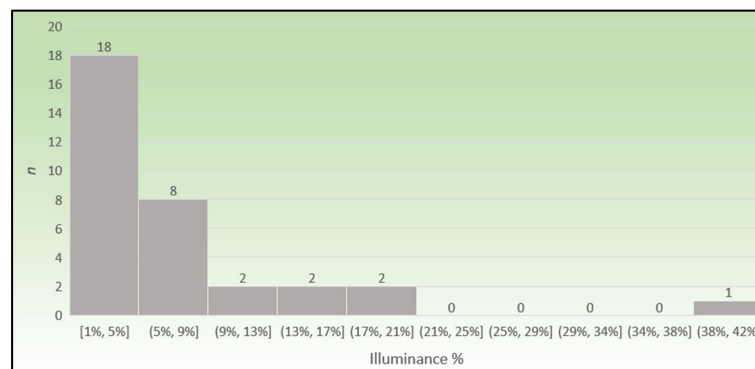


Figure 1414. The results for green light, distributed by illuminance levels in percent.

The Person's Correlation Coefficient is set to $r(31) = .9962$, $p = < .00001$. This concludes that the result is significant and as shown in the graph (Figure 1515) there is a strong positive correlation between the measured illuminance and intensity levels of green light.

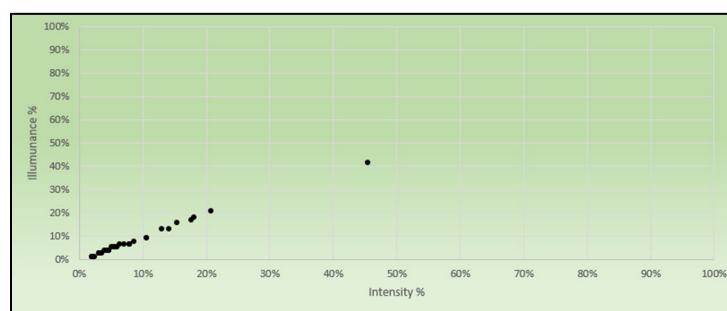


Figure 1515. Correlation between illuminance and intensity in percent of green light.

A two-tailed t-test revealed no significant difference between the illuminance levels of white light compared to the illuminance levels of green light ($t(32) = -1.203, p = 0.238$), see Appendix 11.

The mean for the illuminance levels of white light ($M = 6.8\%$, Variance = 0.3%) was not significantly lower than the mean for the illuminance levels of green light ($M = 7.8\%$, Variance = 0.6%).

To summarize the statistics of the green light the graph that follows shows the mean of the illuminance levels of green light compared to the mean of the illuminance levels of white light (see Figure 1616). Both percentages are calculated according to each color's individual maximum illuminance levels.

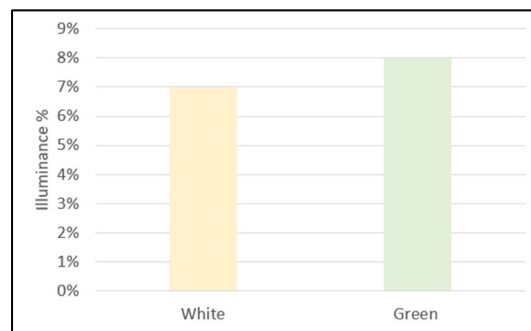


Figure 1616. Mean of illuminance levels in percentage of white and green light. Note that the Y-axis shows the percentage of each colors individual total. 100% illuminance of white is set to 20 lux and 100% of green is set to 7.7 lux.

4.1.4 Blue

The maximum illuminance level (100%) of blue light was measured to 3.3 lux. The mean illuminance level was 22.2% ($N = 33$, Median = 15.2%, $SD = 18.7\%$, range: 3-81.8%), see Appendix 10. The results distributed by illuminance levels in percent are presented in the following histogram, see Figure 1717.

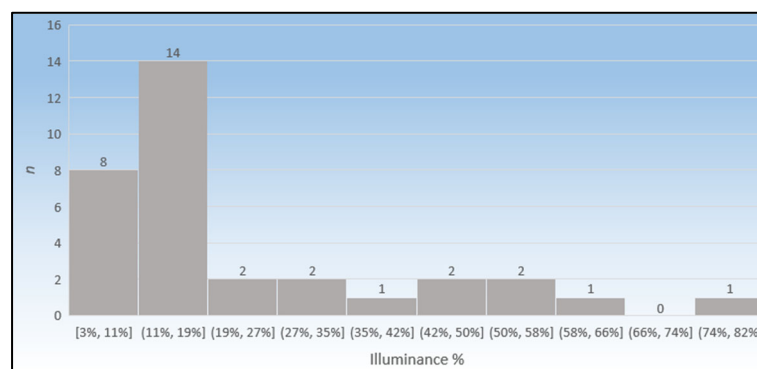


Figure 1717. The results for blue light, distributed by illuminance levels in percent.

The Person's Correlation Coefficient is set to $r(31) = .9977, p = < .00001$. This concludes that the result is significant and as shown in the graph (Figure 1818) there is

a strong positive correlation between the measured illuminance and intensity levels of blue light.

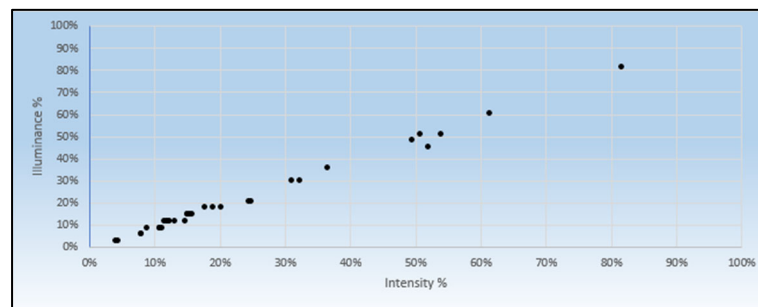


Figure 1818. Correlation between illuminance in % and intensity in % of blue light.

A two-tailed t-test revealed no significant difference between the illuminance levels of white light compared to the illuminance levels of blue light ($t(32) = -5.969, p < .001$), see Appendix 11Appendix .

The mean for the illuminance levels of white light ($M = 6.8\%$, Variance = 0.3%) was significantly lower than the mean for the illuminance levels of blue light ($M = 22.2\%$, Variance = 3.5%).

To summarize the statistics of the blue light, the graph that follows shows the mean of the illuminance levels of blue light compared to the mean illuminance levels of white light (see Figure 1919). Both percentages are calculated according to each color's individual maximum illuminance levels.

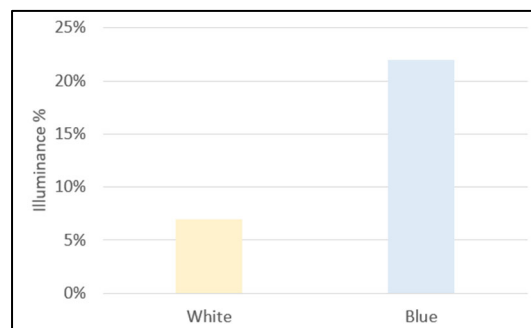


Figure 1919. Mean of illuminance levels in percentage of white and blue light. Note that the Y-axis shows the percentage of each colors individual total. 100% illuminance of white is set to 20 lux and 100% of blue is set to 3.3 lux.

4.1.5 Demographic data

The gender distribution between the participants were 16F and 17M. The following graphs shows the illuminance levels in percent per participant. They are organized according to the levels of white light in order to present a more distinct graph, see Figure 2020.

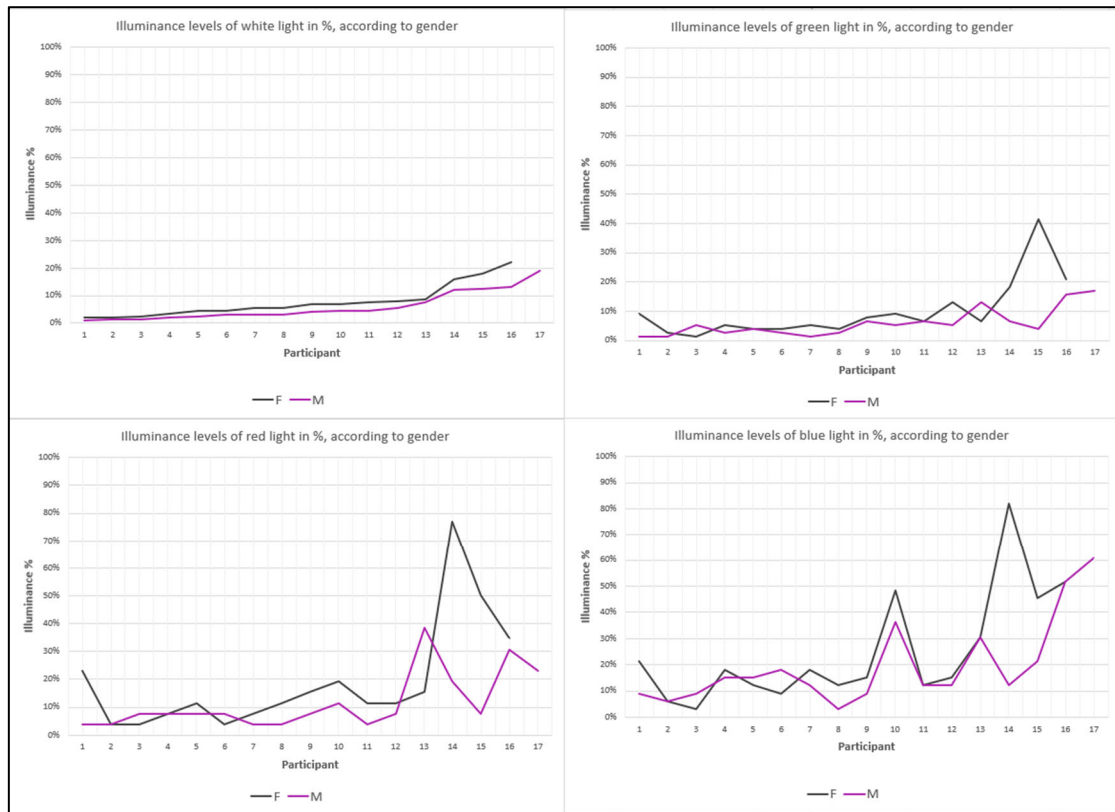


Figure 2020. Illuminance levels in % according to gender.

The mean age of the participants was 26,6Y (*Median* = 25, *Range*: 20-40, *SD* = 5,4). The required illuminance levels in percent per participant are presented in Figure 2121.

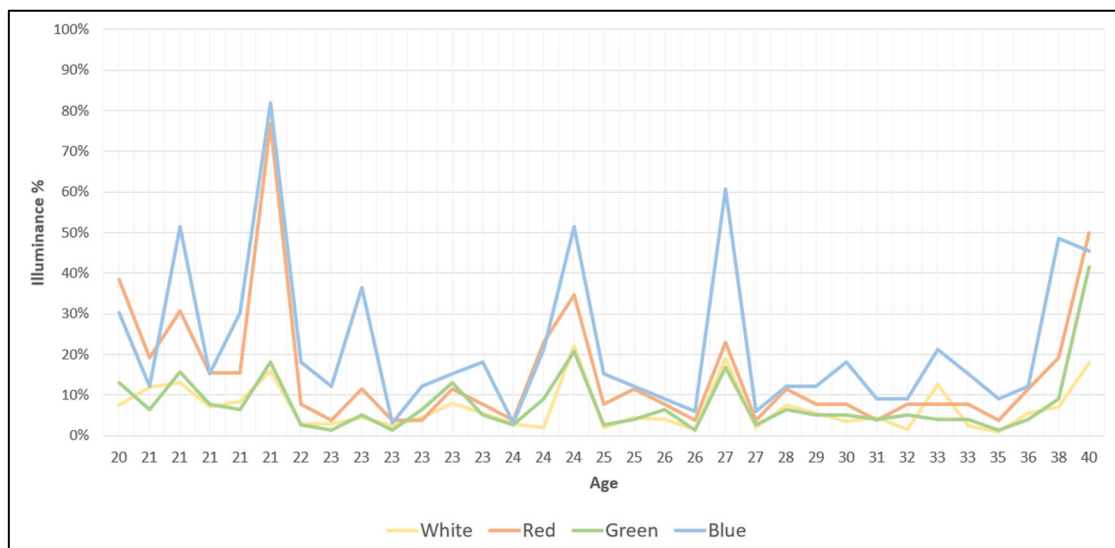


Figure 2121. Illuminance levels in percent according to age.

4.2 Analysis

4.2.1 Correlation between intensity and illuminance

In order to ensure that the measured illuminance was coherent to the dim-levels, the correlation coefficient was calculated for each color. As all four colors showed a strong correlation between illuminance and intensity, it proofed that the measured illuminance was accurate. Therefore, it was presumed reliable to use lux as comparison unit.

4.2.2 Dispersion of result

The following table shows the central tendency as well as the dispersion of the data for each color, see Table 2. The tendency for all colors is that there is a right-skewed distribution of the data. The red light showed the most right skewed data with a first quartile (Q1) at 5.8% and a range of 3.8%-76.9%. Blue light had a similar range but with a higher dispersion of data. The results for the neutral white and green light showed similar Standard Deviation- (*SD*-)values as well as mean, median, min, and Q1 values. The only value which differs is the max value, where the green max was 41.6% versus white 22%.

Table 2. Dispersion of results

	Min	Max	Median	Q1	Mean	Standard Deviation
White light	1%	22%	4.5%	3%	6.8%	5.5%
Red light	3.8%	76.9%	7.7%	5.8%	15.3%	15.8%
Green light	1.3%	41.6%	5.2%	3.2%	7.8%	7.9%
Blue light	3%	81.8%	15.2%	10.6%	22.2%	18.7%

4.2.3 White vs colors

The average illuminance level of each color is compared to the average illuminance level of white in the following graph, see Figure 2222. In order to compare the results, the average illuminance of white has been set to 100%. The results show that in order to achieve the same perceived brightness, more than twice as much red light is required. As former *t*-test showed, there is only a marginal difference between the perceived brightness of green and white light. The highest value was reported with blue light: more than three times as much as white light was required to reach the same perceived brightness.

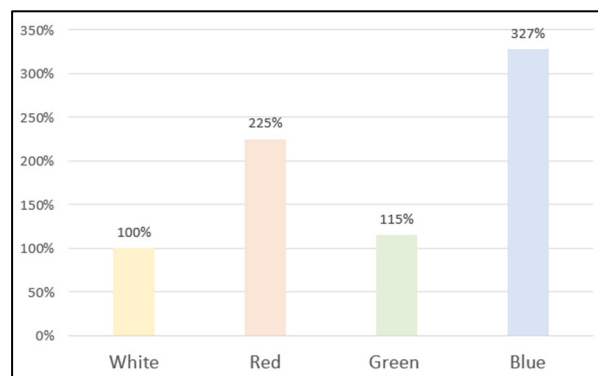


Figure 2222. Percentage of colored light required, compared to white light, to achieve the same perceived brightness, according to illuminance in percent.

4.2.4 Gender

The study showed that female participants in general required slightly higher levels of illuminance on both white and colored light. As the gender division in this study is set to 49.5% female and 50.50% male, the result is considered to be representative. As this parameter is not part of the research question, it will not be further discussed.

4.2.5 Age

The results showed no correlation between age and required illuminance levels, see Figure 2323.

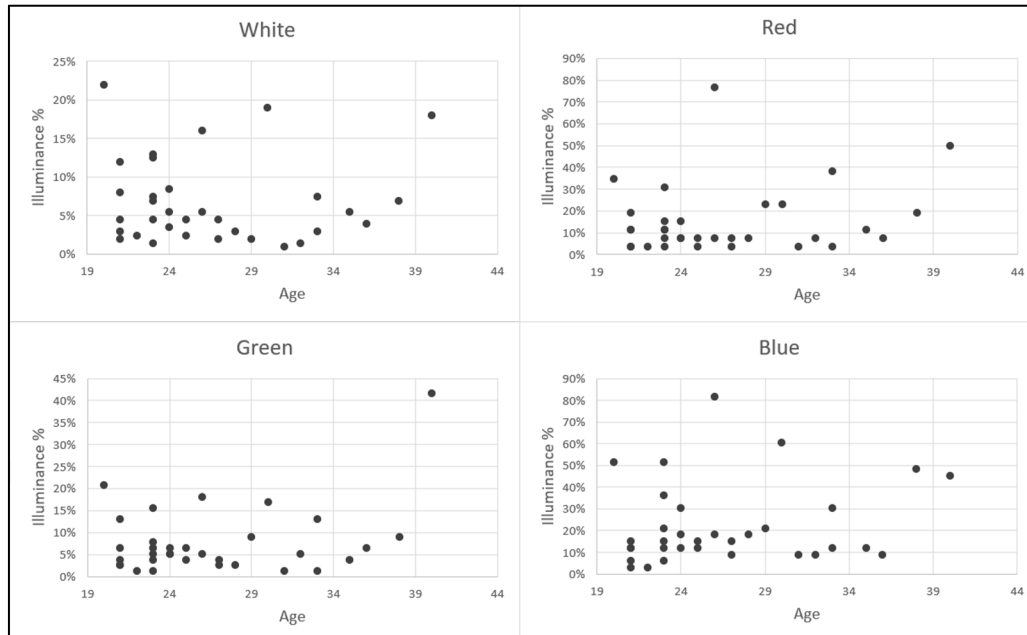


Figure 2323. Correlations between age and required illuminance levels.

5 Discussion

5.1 Result discussion

This study investigates what levels of colored light is needed to achieve the same perceived brightness as with white light and is performed with LED on point sources. The results showed that nearly three times as much blue light (λ_p 464nm), nearly twice as much red light (λ_p 634nm), and nearly the same amount of green light (λ_p 519nm), were required to achieve the same perceived brightness as with white light (CCT 4000K, Duv -0.0007).

The results showed clearly that the majority of the participants needed low light levels to perform the Landolt C test within all colors, including the neutral white light. There was a difference between the dispersion of data among the colors though: The results from the green and white light were unambiguous and showed a low dispersion of data. The red and blue light had a higher dispersion of data, which indicated a lower precision of the results. Within the results of red, green, and blue light, outliers on the right end were found, which affected the mean-values marginally and the range-value considerably. It also affects the relationships between red, green, blue, and white light. The outliers in the data of this study are considered to be indicators of individual differences of the participants.

There were differences in required light levels for different colors of light that correlated with gender but not with age. As it is not part of the aim of the study, no further discussion will be held.

The result concurs with several studies that showed that the perceived brightness depends on the spectral distribution of the light (Berman et al., 1996; Hwang et al., 2012; Wardhani et al., 2022, Bornstein 1975). The results of the current study showed that less green light was required compared to red and blue light, which is in line with the results of Bornstein (1975) and Hwang et al., (2012). The levels of green light were similar to the levels of white light, which concurs with results of Olguntürk (2015). The blue light required the highest percentage of its maximum illuminance, which is in line with the research by Leube et al., (2018), Pokorny et al., (1968), and Van Buren et al., (2018).

One study that contradicts the current result, showed that blue light (λ_p 490nm) was perceived as brighter than white and red (λ_p 670nm) light of the same intensity (Shlaer et al., 1941). The main difference was the adaptation time which affects the exponent of the power law determining the ratio between brightness and luminance (see equation 3) (Boyce, 2014). In the study by Shlaer et. al. (1941) the adaptation time was long enough to let the participants “become completely adapted” (p. 554) between each intensity level of the stimuli, and therefore it was possible to use low levels of intensity. In the current study an adaptation time of 30 seconds was considered sufficient as in real-life situations, there are rarely 10 minutes of darkness between different light colors. This is estimated to be one of the main reasons why the results from Shaler, et. al. (1941) differ from the current study. When using light with low intensity and short wavelength, the rods activate and with a simultaneously use of cones, the visual function increases (the *Purkinje phenomenon* (Hunt & Pointer, 2011)), which may

explain why the blue light was perceived as brighter than the white and red light (Shlaer et al., 1941).

Visual field is another parameter that may affect the results when studying the perceived brightness of colored light. In a study by Caberletti et al., (2010) blue light (λ_p 471nm) was shown to be perceived brighter than orange light (λ_p 605). In the study by Caberletti et al., (2010) a visual field of 135° was used which resulted in that the stimulus was registered in the peripheral part of the retina (Boyce, 2014). In the current study, the visual stimuli had a retinal image size of $R \approx 0.105\text{mm}$ and thereby it was registered in the foveola ($\varnothing \approx 0.3\text{mm}$ (Aries et al., 2022; Boyce, 2014)) of the participants. Due to the distribution of the photoreceptors in the retina (the S-cones are located outside the foveola (Weale, 1953)) this caused a reduced sensitivity to blue light, compared to if the peripheral part of the retina had been used (Boyce, 2014).

5.2 Method discussion

The choice of method (experiment with *method of limits*) was considered to be adequate since it answered the research questions and is one of the traditional methods of psychophysics (Gescheider, 1997). Different parameters of the experiment affected the reliability and validity.

The first parameter was the sample group that had to fulfill certain criteria to participate in the experiment. They had to pass a color vision test and also had to be between 18-40 years old. The gender division in the 33 participants were 48,5%F/51,5%M, which is to consider to be as equal as possible. This gives the study a high external validity (Gustavsson & Säfsten, 2019).

The second parameter was the procedure. As the measurements took place inside the apparatus, and all the variables included were strictly controlled, every test was performed in the same way (except randomization of the order of colors), and the reliability is calculated to be high (Gustavsson & Säfsten, 2019). However, the validity may have decreased due to the adaptation time between each stimulus, (as earlier discussed) as it is one of the aspects that affects the critical stimulus value (Gescheider, 1997).

The third parameter was the apparatus and its components. One of the components was the light sources. The near-monochromatic light ensured that the colors would contain specific wavelengths in a cluster. The λ_p for each light color is specified in the Method-section together with the SPD, CCT and Duv of the white light. This reinforces the internal validity as well as the reliability. As various studies have shown that the perceived brightness of light depends on the spectral distribution (Berman et al., 1990; Boyce, 2014; Hwang et al., 2012), the result of the current study is only generalizable on light sources with similar characteristics. In Table 3. *The λ_p of the different cones of the human eye, and light sources used in the experiment* the λ_p of each light source is compared to the sensitivity peak of each cone. It shows that the peak for the blue and green light lies near the peak of the respective cones, however, the red light lies slightly further away from the peak of the L-cones, which indicates that there might have been a reduced sensitivity regarding the red light. This may have affected the results, and thereby the internal as well as the external validity.

Table 3. The λ_p of the different cones of the human eye, and light sources used in the experiment.

	S-cones	Blue light	M-cones	Green light	L-cones	Red light
λ_p	450 nm	464 nm	525 nm	519 nm	575 nm	634 nm

Another component was the psychophysical criterion; visual acuity with Landolt C test. Studies have shown that the pupil size affects both the perceived brightness (Sulutvedt et al., 2021) as well as the visual acuity (Shlaer et al., 1941). Problematically, they are being affected in diametrically opposite ways; according to Sulutvedt et al., (2021) a contracted pupil decreases the perceived brightness, while Shlaer et al., (1941) states that it increases the visual acuity. Blue light has been shown to decrease and red light to increases the size of the pupil (Wardhani et al., 2022). This causes a conflict in the method of the current study where visual acuity was used as a reference to investigate the perceived brightness.

The fourth parameter was the tools of measurement, the lux-meter. As earlier studies have discussed, the accuracy is lacking when measuring near-monochromatic light with methods and devices based on the $V(\lambda)$, such as luxmeters and luminance camera (Padgham, 1971; Roufs, 1978). Roufs (1978) states that the “[...] discrepancy between luminance and brightness increases with the saturation of the light.” (p.16). Red, green, and blue light are stated to be perceived as brighter than less saturated colors (Boyce, 2014; Hwang et al., 2012). This implicates that in a real-life situation, measuring near-monochromatic light with a luxmeter (or similar photometric tool intended to measure light-levels, based on the $V(\lambda)$), would not give adequate results in terms of perceived brightness (Padgham, 1971). Padgham (1971) states that the international agreement of photometry "is based on an arbitrary definition of luminous flux which is generally satisfactory, but for which there is ample evidence of giving seriously misleading results on the appearance of colors of high purity" (p.588). The conclusion is that studies regarding colored light, using photometric units as reference values, demonstrates the deficiency of the photometric system rather than showing adequate results regarding the perceived brightness of colored light (Padgham, 1971).

Since all photometric quantities are based on the $V(\lambda)$, none would be accurate to use when planning colored light. In the current study, a more reliable method would have been the use of radiometry in order to measure the light levels in an objective way. As the direct observations in this study used a visual acuity test to define light levels, and the luxmeter was used to produce a comparable value, the mentioned difficulties with the photometric system were practically omitted. The strong correlation between the dim-values and the measured lux-values supports the method of measurement and thereby strengthens the reliability.

6 Conclusion

This study aimed to investigate the perceived brightness of colored light. The colors which were studied were red, green, and blue. Neutral white light was used as a reference. The findings of the study are:

- The perceived brightness of the light was affected by the spectral distribution.
- Green light was perceived as brighter than red and blue light. The blue light was perceived as less bright than the other lights.
- It is complex to implement the results of the study as there is no current agreement of how to measure colored light. According to several studies there are serious doubts about whether photometry is suitable for measuring colored light, and there is a lack of complementary units on the market. See discussion further down.

Based on the results of the current study and previous research, the conclusion is that the perceived brightness is affected by different parameters, among them the size of the visual field, the spectral distribution (Berman et al., 1996; Bornstein, 1975; Caberletti et al., 2010; Hwang et al., 2012). As there are various parameters that affect the relationship between brightness and luminance (the stimulus critical value function), the results of this study are limited and may only apply in similar situations. The current study used a visual target that was registered in the foveal part of retina which implicated that the results are only applicable on smaller visual objects. Some examples may be when planning near-monochromatic light for detail work such as surgery or manufacturing. Other areas may be car interiors or decorative purposes, or whenever colored light is preferable to white light. It is of importance to consider that, whenever using the result as support of planning, the used reference light was a LED with a CCT of 4000 K.

Colored light has been shown to affect the visual acuity and to cause glare (Roaf & Sherrington, 1930; Shlaer et al., 1941; Yang et al., 2018), which makes it important to use correct levels of intensity. Therefore the result of this study may be useful to optimize the visual ergonomics. From a sustainability point of view, by planning correct levels of colored light instead of estimating, energy can be saved (Yang et al., 2018; Zhang et al., 2022).

The use of colored light is increasing in various fields and the lack of guidelines and standards is tangible. As earlier mentioned, there are various parameters affecting the perceived brightness. Therefore, further research is suggested using a different visual field, spectral distribution, intensity levels and backlit areas, such as point sources or luminous surfaces.

It is also suggested that further research will be performed regarding photometry and near-monochromatic light, since many studies showed that photometry is not giving adequate result when measuring colored light. One option might be using radiometry. But as it is not conventional to mark luminaires or light sources with radiometric quantities, the most suitable option would be the input power, watt. It is recommended though, that further research is executed first.

The study showed differences between the genders regarding the perceived brightness. Even though this was not part of the aim of the study, the results were enough clear to indicate that further research is needed. This may be of importance when choosing sample groups in future research within the psychophysical field.

References

- American Psychological Association. (n.d.). *difference threshold*, *APA Dictionary of Psychology*. Retrieved March 24, 2023, from <https://dictionary.apa.org/difference-threshold>
- Arbetsmiljöverket. (2022, March 17). *Ljus och belysning*. <https://www.av.se/inomhusmiljo/ljus-och-belysning/#7>
- Aries, M. , Beute, F. , & Wärnström-Lindh, U. ., (2022). *Light for health and well-being - Course booklet*.
- B H Crawford. (1949). The Scotopic Visibility Function. *Proceedings of the Physical Society. Section B*, 62(5), 321. <https://doi.org/10.1088/0370-1301/62/5/305>
- Behar-Cohen, F., Martinsons, C., Viénot, F., Zissis, G., Barlier-Salsi, A., Cesarini, J. P., Enouf, O., Garcia, M., Picaud, S., & Attia, D. (2011). Light-emitting diodes (LED) for domestic lighting: Any risks for the eye? *Progress in Retinal and Eye Research*, 30(4), 239–257. <https://doi.org/10.1016/j.preteyeres.2011.04.002>
- Berman, S. M., Fein, G., Jewett, D., Benson, B., Law, T., & Myers, A. (1996). Luminance-Controlled Pupil Size Affects Word-Reading Accuracy Energy and Environment Division. *Journal of the Illuminating Engineering Society*, 25(1). <https://escholarship.org/uc/item/51n8k3kq>
- Berman, S. M., Feinl, G., Jewett, D. L., & Ashford, F. (1993). *Luminance Controlled Pup;1 Size Affects Landolt C Task Performance*.
- Berman, S. M., Jewett, D. L., Fein, G., Saika, G., & Ashford, F. (1990). Photopic luminance does not always predict perceived room brightness. *Lighting Research & Technology*, 22(1), 37–41. <https://doi.org/10.1177/096032719002200103>
- Bornstein, M. H. (1975). On Light and the Aesthetics of Color: Lumia Kinetic Art. *Leonardo*, 203–212. <https://about.jstor.org/terms>
- Boyce, P. R. (2014). *Human Factors in Lighting Third Edition* (Third). Taylor & Francis Group, LLC.
- Caberletti, L., Elfmann, K., Kummel, M., & Schierz, C. (2010). Influence of ambient lighting in a vehicle interior on the drivers perceptions. *Lighting Research and Technology*, 42(3), 297–311. <https://doi.org/10.1177/1477153510370554>
- Cancer Research UK. (2014). Diagram showing parts of the eye CRUK 326.svg. In *Wikimedia Commons*. Wikimedia Commons.
- CC Public domain. (2012). *PlanckianLocus*. [illustration].Wikimedia Common. <https://commons.wikimedia.org/wiki/File:PlanckianLocus.png>. [March 21st 2023]
- Falmagne, J.-C. (1985). *Elements of Psychophysical Theory*. Oxford University Press, Incorporated. <http://ebookcentral.proquest.com/lib/jonhh-ebooks/detail.action?docID=281327>

- Federal Trade Commission Consumer Advice. (2021, May). *Shopping for Light Bulbs*.
- Gescheider, G. (1997). *Psychophysics: the fundamentals* (3rd ed.). Lawrence Erlbaum Associates.
- Gibson, & Tyndall. (1923). The visibility of radiant energy. *Journal of the Franklin Institute*, 196(5), 680–681. [https://doi.org/https://doi.org/10.1016/S0016-0032\(23\)90573-9](https://doi.org/https://doi.org/10.1016/S0016-0032(23)90573-9)
- Gold, V. (Ed.). (2019). *The IUPAC Compendium of Chemical Terminology*. International Union of Pure and Applied Chemistry (IUPAC). <https://doi.org/10.1351/goldbook>
- Guild, J., & Inst, P. , F. (1931). THE COLORIMETRIC PROPERTIES OF THE SPECTRUM. *Philosophical Transactions of the Royal Society of London. Series A, Containing Papers of a Mathematical or Physical Character* , 230, 149–187. <https://doi.org/http://doi.org/10.1098/rsta.1932.0005>
- Gustavsson, M., & Säfsten, K. (2019). *Forskningsmetodik för ingenjörer och andra problemlösare*. Studentlitteratur.
- Hunt, R. , W. , G., & Pointer, M. , R. (2011). *Measuring Colour*. John Wiley & Sons, Incorporated.
- Hwang, T., Lee, D. G., & Kim, J. T. (2012). Optimal illuminance of seven major lighting colours in LED: Focus on occupant comfort and communication in an indoor environment. *Indoor and Built Environment*, 21(1), 122–128. <https://doi.org/10.1177/1420326X11420013>
- Ishihara, S. (1979). *Tests for Colour-blindness Tokyo*. Kanehara Shuppan Co.
- Ives, H. E. (1912). XII. Studies in the photometry of lights of different colours. *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science*, 24(139), 149–188. <https://doi.org/10.1080/14786440708637317>
- Khan, T. , Q., Bodrogi, P., Vinh, Q. , T., Winkler, H., & (Eds.). (2015). *LED Lighting: Technology and Perception* (Khanh & Tran Quoc, Eds.). Wiley-VCH Verlag GmbH & Company KGaA.
- Leube, A., Kostial, S., Alex Ochakovski, G., Ohlendorf, A., & Wahl, S. (2018). Symmetric visual response to positive and negative induced spherical defocus under monochromatic light conditions. *Vision Research*, 143, 52–57. <https://doi.org/10.1016/j.visres.2017.12.003>
- Lu, Z.-L., & Doshier, B. (2013). *Visual Psychophysics : From Laboratory to Theory*. MIT Press. <http://ebookcentral.proquest.com/lib/jonhh-ebooks/detail.action?docID=3339691>
- Montgomery, D. , C. (2013). *Design and analysis of experiments* (8th ed.). Wiley.
- Ngai, P. Y. (2000). The relationship between luminance uniformity and brightness perception. *Journal of the Illuminating Engineering Society*, 29(1), 41–50. <https://doi.org/10.1080/00994480.2000.10748480>

- Nyquist, H. (2021). *Statistikens grunder : vetenskap, empiriska undersökningar och statistisk analys* (Andra upplagan). Studentlitteratur.
- Ohta, N., & Robertson, A. R. (2005). *Colorimetry Fundamentals and Applications*. John Wiley & Sons Ltd.
- Olguntürk, N. (2015). Effects of coloured lighting on the perception of interior spaces. *Perceptual and Motor Skills*, 120(1), 183–201. <https://doi.org/10.2466/24.PMS.120v10x4>
- Oxford Reference. (2023, March 21). *monochromatic radiation*. Oxford Reference. <https://doi.org/10.1093/oi/authority.20110803100206892>
- Padgham, C. A. (1971). THE DIRECT ESTIMATION OF THE LUMINOSITY OF COLOURED LIGHT SOURCES. In *Vision Res* (Vol. 11). Pergamos Press.
- Pokorny, J., Graham, C. H., & Lanson, R. N. (1968). Effect of Wavelength on Foveal Grating Acuity. *Journal of the Optical Society of America*, 58(10), 1410–1414. <https://doi.org/10.1364/JOSA.58.001410>
- Rea, M. S., & Freyssinier, J. P. (2013). White lighting. *Color Research and Application*, 38(2), 82–92. <https://doi.org/10.1002/col.20738>
- Roaf, H., & Sherrington, C. (1930). Visual Acuity in Light of Different colours. *Proceedings of the Royal Society of London. Series B, Containing Papers of a Biological Character*, 106(744), 276–292. <https://doi.org/10.1098/rspb.1930.0028>
- Roufs, J. A. J. (1978). *Light as a true visual quantity: principles of measurement*. www.tue.nl/taverne
- Schanda, J., Morren, L., Rea, M., Rositani-Ronchi, L., & Walraven, P. (2002). Does lighting need more photopic luminous efficiency functions? *Lighting Research & Technology*, 34(1), 69–76. <https://doi.org/10.1191/1365782802li031oa>
- Shlaer, S., Smith, E. , L., & Chase, A. , M. (1941). *Visual acuity and illumination in different spectral regions*. <http://rupress.org/jgp/article-pdf/25/4/553/1239272/553.pdf>
- Stockman, A. (2003). Colorimetry. In *Encyclopedia of Applied Physics* (pp. 207–226).
- Stockman, A. (2019). Cone fundamentals and CIE standards. In *Current Opinion in Behavioral Sciences* (Vol. 30, pp. 87–93). Elsevier Ltd. <https://doi.org/10.1016/j.cobeha.2019.06.005>
- Strasburger, H., Rentschler, I., & Jüttner, M. (2011). Peripheral vision and pattern recognition: A review. *Journal of Vision*, 11(5). <https://doi.org/10.1167/11.5.13>
- Sulutvedt, U., Zavagno, D., Lubell, J., Leknes, S., de Rodez Benavent, S. A., & Laeng, B. (2021). Brightness perception changes related to pupil size. *Vision Research*, 178, 41–47. <https://doi.org/10.1016/j.visres.2020.09.004>
- Swedish Standards Institute. (2014). *Ljus och belysning - Belysning av arbetsplatser - Del 2: Arbetsplatser utomhus*. (SS-EN 12464-2:2014). Svenska institutet för

- p>standarder.
- <https://www-sis-se.proxy.library.ju.se/produkter/ergonomi-fb23d4ad/ergonomi--ljus-och-belysning/ssen1246422014/>
- Swedish Standards Institute. (2022). *Ljus och belysning - Belysning av arbetsplatser - Del 1: Arbetsplatser inomhus*. (SS-EN 12464-1:2021). Svenska institutet för standarder. <https://www-sis-se.proxy.library.ju.se/produkter/byggnadsmaterial-och-byggnader/belysning/inomhusbelysning/ss-en-12464-12021-c7ee7e9c/>
- Trafikverket. (2022). *VGU Vägar och gators utformning*. (Publikation 2022:001). <http://trafikverket.diva-portal.org/smash/get/diva2:1621114/FULLTEXT02.pdf>
- Van Buren, J. P., Wake, J., McLaughlin, J., LaPorta, A. J., Enzenauer, R. W., & Calvano, C. J. (2018). Optimizing Tactical Medical Performance: The Effect of Light Hue on Vision Testing. *Journal of Special Operations Medicine*, 18(2), 75. <https://doi.org/10.55460/VZ0Q-Y41S>
- Wald, G. (1945). Human vision and the spectrum. *Science*, 101(2635), 653–658. <https://doi.org/doi:10.1126/science.101.2635.653>
- Wandell, B. A. (1995). *Foundations of vision*. Sinauer Associates.
- Wardhani, I. K., Boehler, C. N., & Mathôt, S. (2022). The influence of pupil responses on subjective brightness perception. *Perception*, 51(6), 370–387. <https://doi.org/10.1177/03010066221094757>
- Ware, C. (2013). Color. In *Information Visualization* (pp. 95–138). Elsevier. <https://doi.org/10.1016/B978-0-12-381464-7.00004-1>
- Ware, C. (2021). Lightness, Brightness, Contrast, and Constancy. In *Information Visualization* (pp. 69–94). Elsevier. <https://doi.org/10.1016/b978-0-12-812875-6.00003-7>
- Weale, R. , A. (1953). SPECTRAL SENSITIVITY AND WAVELENGTH DISCRIMINATION OF THE PERIPHERAL RETINA. *J. Physiol. (1953)*, 119, 170–190.
- Yang, Y., Luo, R. M., & Huang, W. J. (2018). Assessing glare, Part 3: Glare sources having different colours. *Lighting Research and Technology*, 50(4), 596–615. <https://doi.org/10.1177/1477153516676640>
- Yeung, M., Dromey, B., Rödel, C., Bierbach, J., Wünsche, M., Paulus, G., Hahn, T., Hemmers, D., Stelzmann, C., Pretzler, G., & Zepf, M. (2013). Near-monochromatic high-harmonic radiation from relativistic laser-plasma interactions with blazed grating surfaces. *New Journal of Physics*, 15. <https://doi.org/10.1088/1367-2630/15/2/025042>
- Zhang, Z., Fort Mir, J. M., & Mateu, L. G. (2022). The Effects of White versus Coloured Light in Waiting Rooms on People’s Emotions. *Buildings*, 12(9). <https://doi.org/10.3390/buildings12091356>

Appendices

Appendix 1

Ishihara Color-vision test

Appendix 2

Demographic data

Appendix 3

Consent-papers

Appendix 4

Room description

Appendix 5

Product sheet of LED-strip

Appendix 6

Landholt C-test

Appendix 7

Data-White light

Appendix 8

Data-Red light

Appendix 9

Data-Green light

Appendix 10

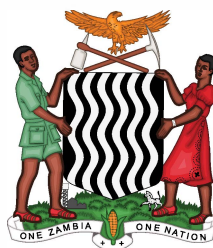
Data-Blue light

Appendix 11

T-test

Appendix 1

Ishihara Color-vision test



ISHIHARA
CHARTS

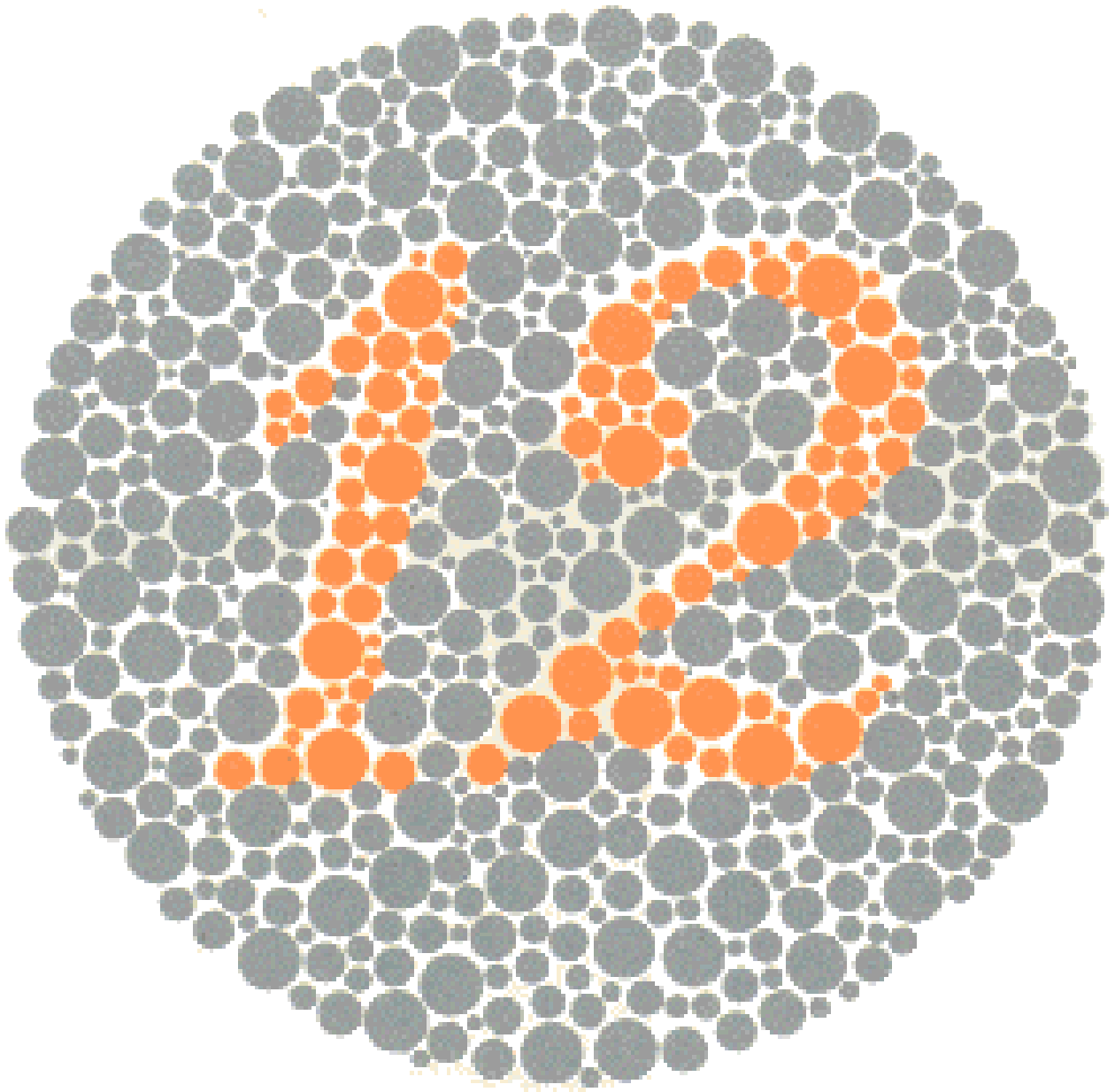


USAID
FROM THE AMERICAN PEOPLE

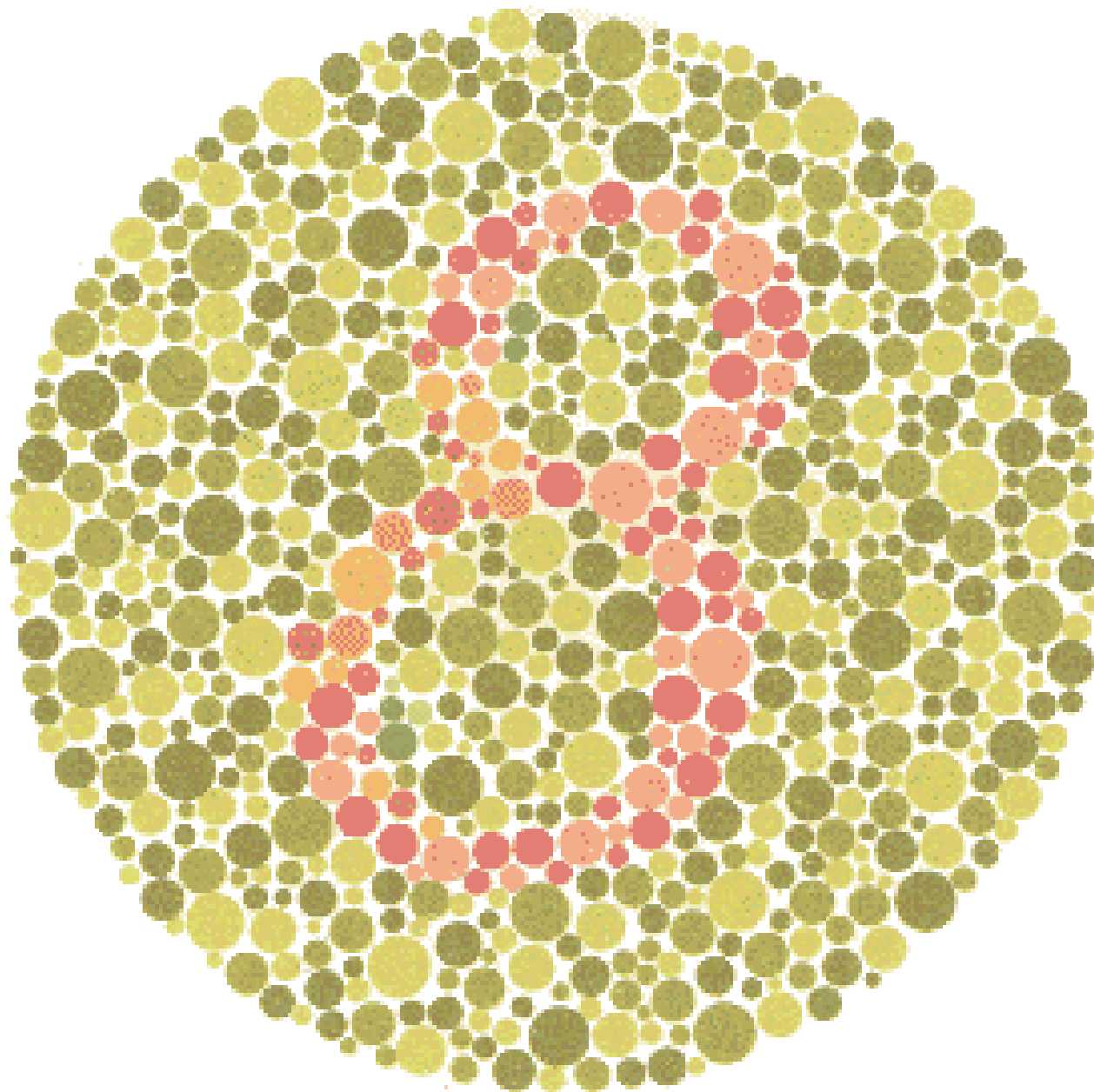
fhi360
THE SCIENCE OF IMPROVING LIVES

CHALLENGE **TB**

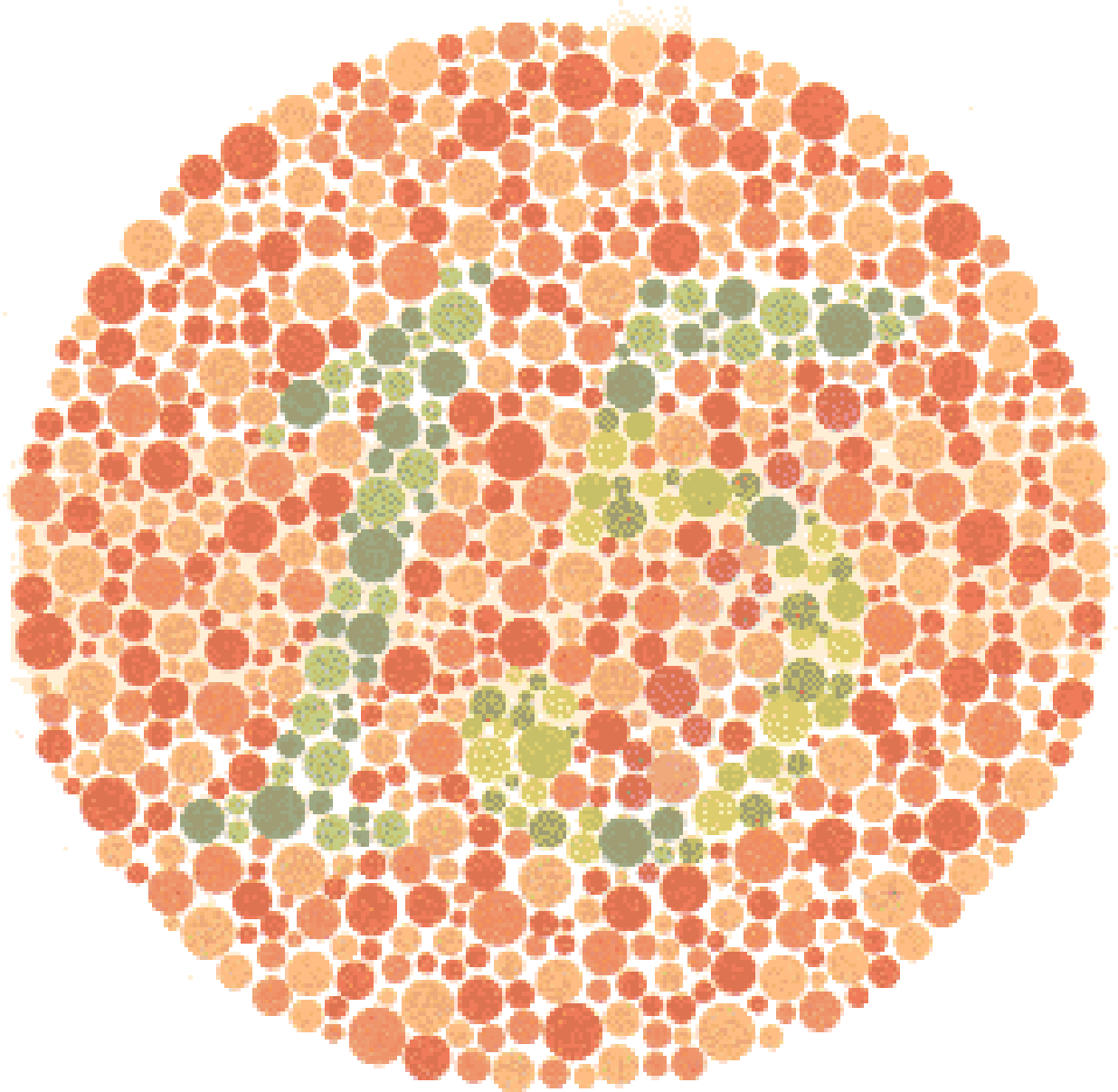
ISHIHARA COLOR BLINDNESS TEST PLATE 1



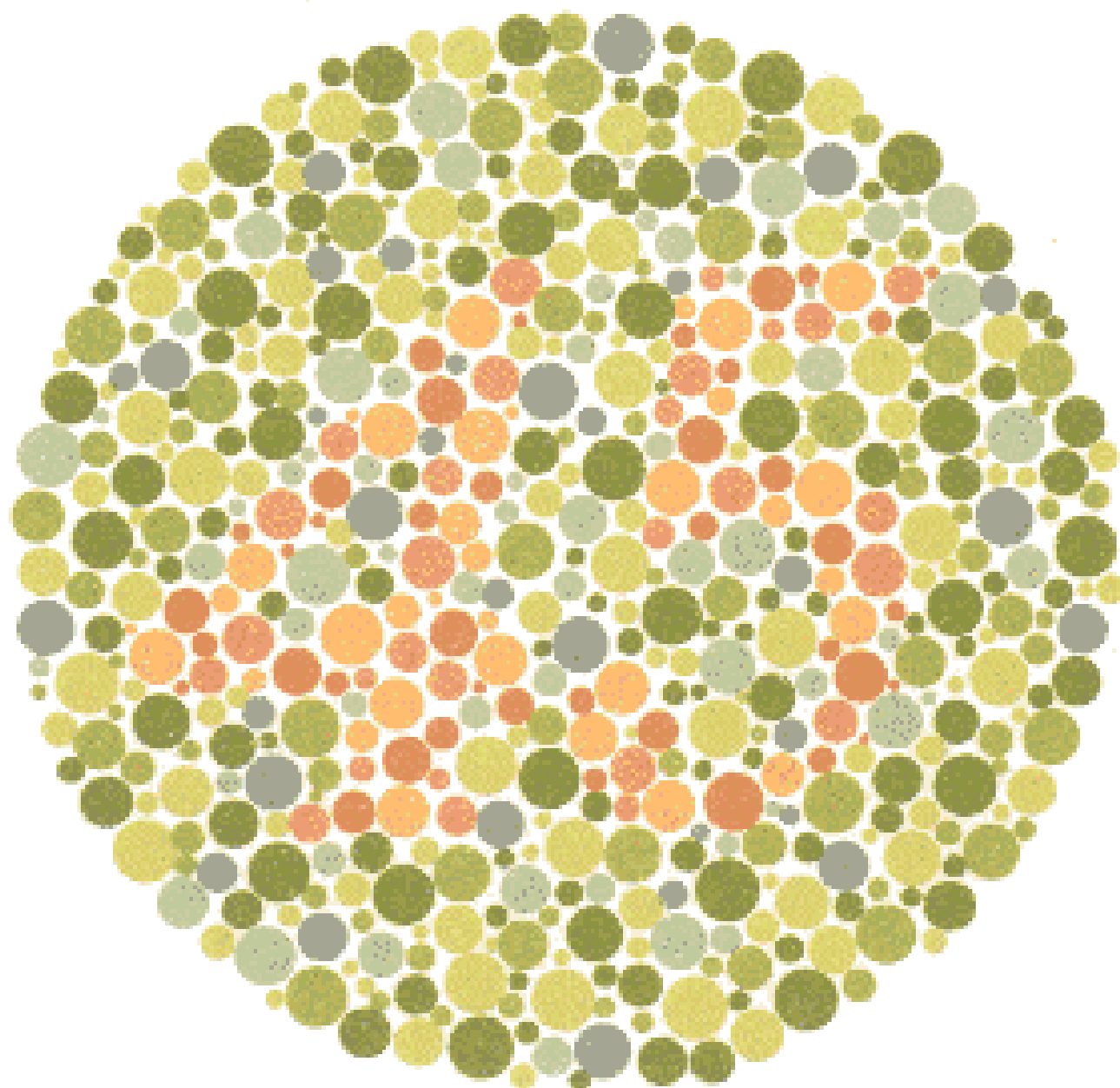
ISHIHARA COLOR BLINDNESS TEST PLATE 2



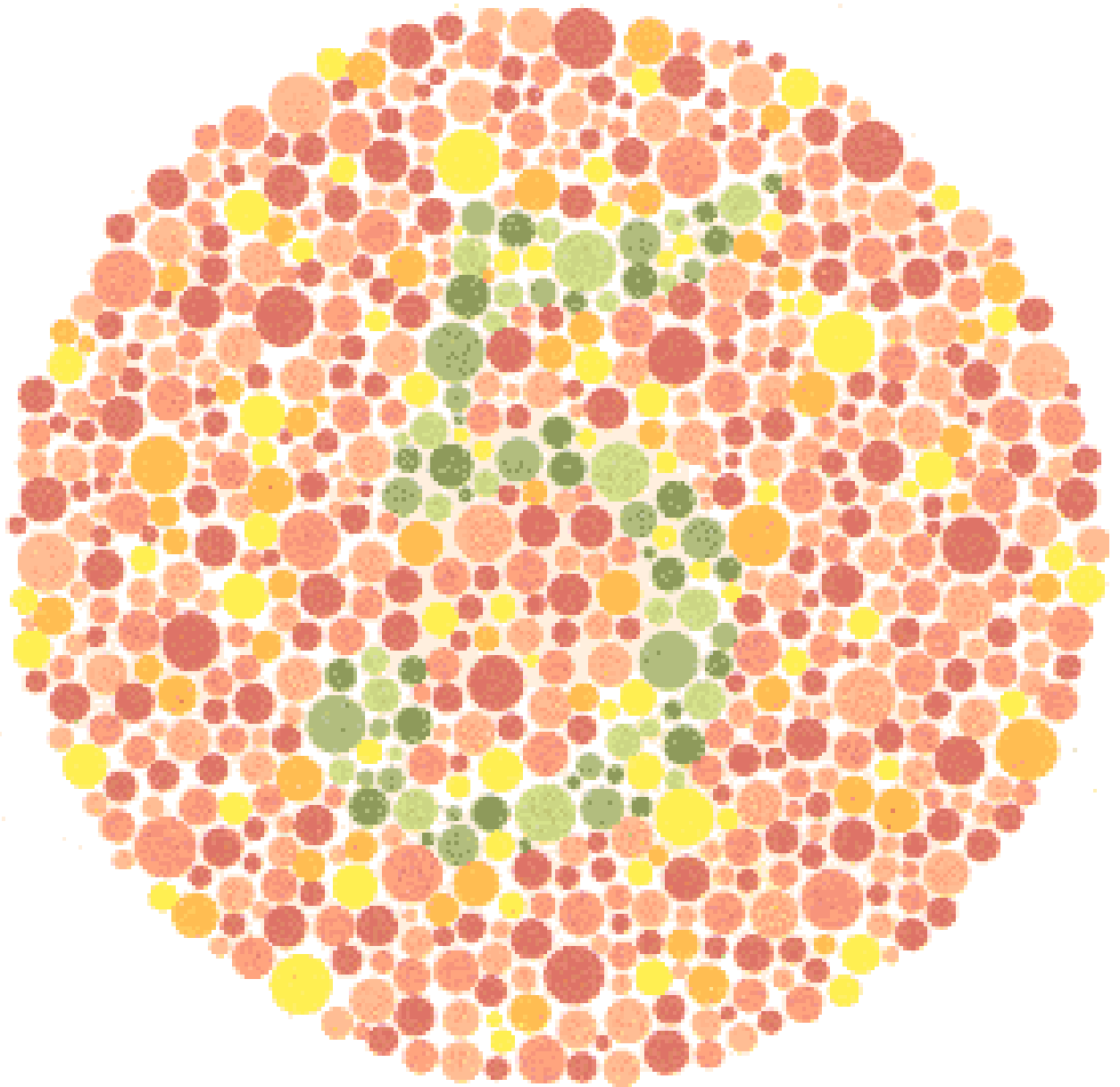
ISHIHARA COLOR BLINDNESS TEST PLATE 6



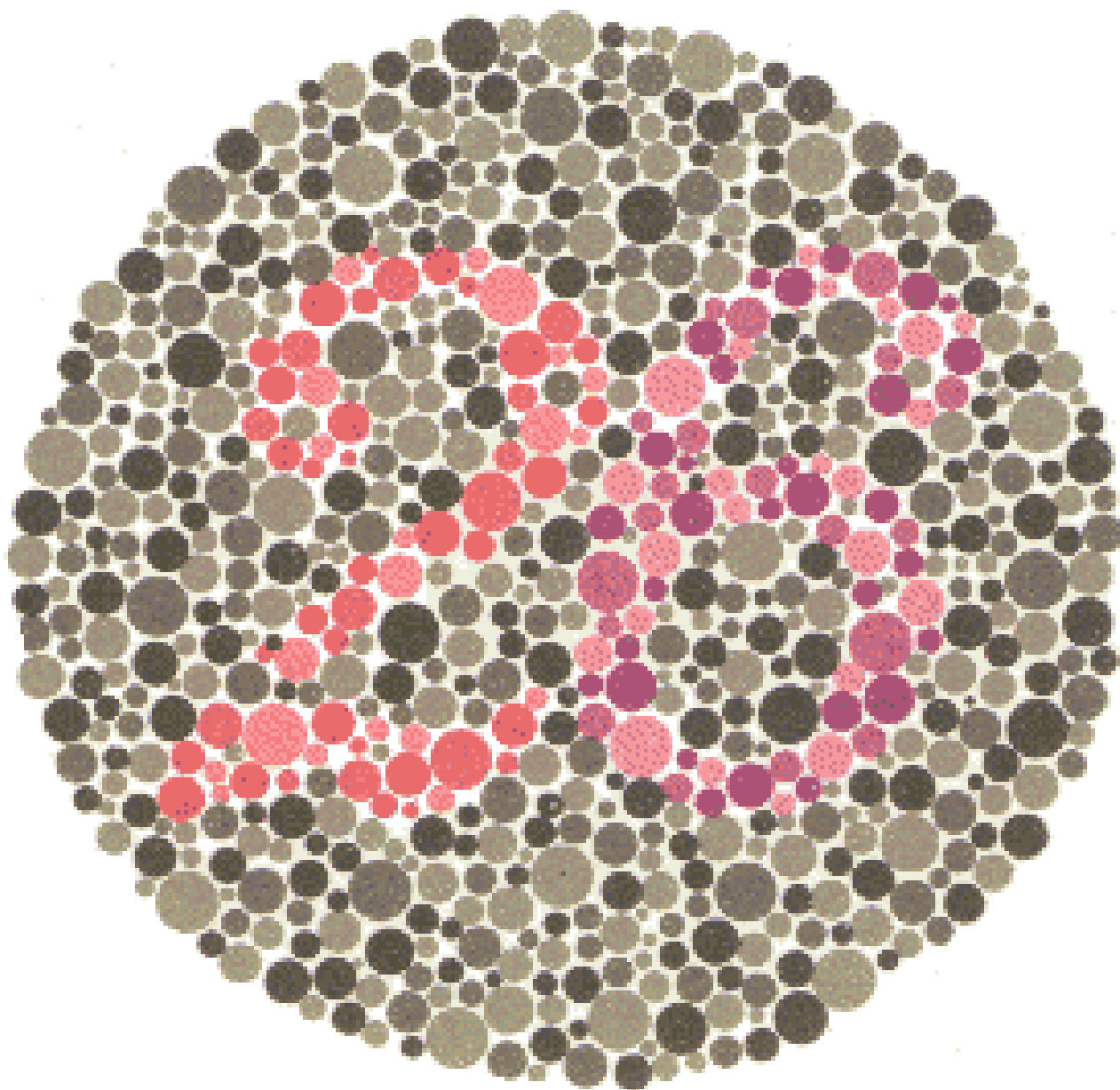
ISHIHARA COLOR BLINDNESS TEST PLATE 9



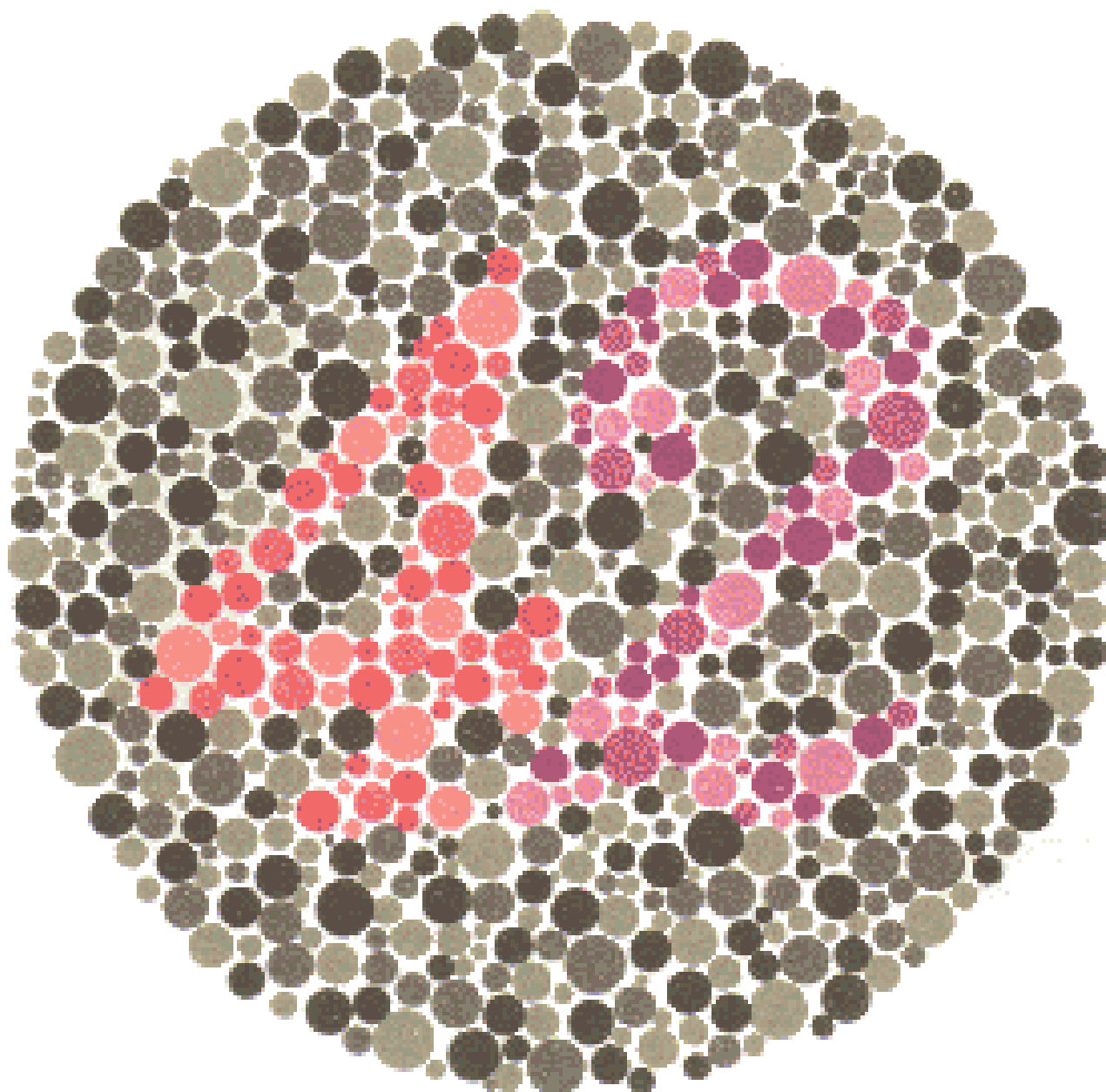
ISHIHARA COLOR BLINDNESS TEST PLATE 10



ISHIHARA COLOR BLINDNESS TEST PLATE 16



ISHIHARA COLOR BLINDNESS TEST PLATE 17



Appendix 2

Demographic data

Participant	Date	Time	Age	Gender	Occupation	Visual aid?
M201	2023-03-06	14:44	33	M	Lightindesigner student	0
M102	2023-03-07	09:20	21	M	Lightindesigner student	0
M103	2023-03-07	09:35	23	M	Lightindesigner student	X
F104	2023-03-07	09:48	23	F	Lightindesigner student	0
F105	2023-03-07	09:58	24	F	Lightindesigner student	0
F206	2023-03-07	10:09	26	F	Lightindesigner student	X
M207	2023-03-07	11:00	28	M	Lightindesigner student	0
M208	2023-03-07	11:14	33	M	Lightindesigner student	0
M109	2023-03-07	11:30	23	M	Byggingenjör	0
F110	2023-03-07	11:48	22	F	Byggteknik	0
M111	2023-03-07	11:55	25	M	Bygnadutformning	0
F112	2023-03-07	12:05	21	F	Byggteknik	0
F213	2023-03-07	12:24	26	F	Lightindesigner student	0
M114	2023-03-07	12:40	21	M	Logistik	0
F215	2023-03-07	12:50	29	F	BIM-master	0
F116	2023-03-07	13:07	20	F	Lightindesigner student	0
M217	2023-03-07	13:21	27	M	Lightindesigner student	0
F118	2023-03-07	13:30	21	F	Lightindesigner student	0
M319	2023-03-07	14:06	36	M	BIM-master	0
M120	2023-03-07	14:15	23	M	BIM-master	0
M221	2023-03-07	14:28	30	M	Lightindesigner student	X
F122	2023-03-07	14:42	21	F	Lightindesigner student	0
F123	2023-03-07	14:53	23	F	Lightindesigner student	0
M124	2023-03-07	15:05	24	M	Lightindesigner student	X
F125	2023-03-07	15:18	24	F	Lightindesigner student	X
F226	2023-03-07	15:28	27	F	Lightindesigner student	X
M227	2023-03-07	15:38	32	M	BIM-master	0
M128	2023-03-07	15:50	23	M	BIM-master	0
M129	2023-03-07	16:00	25	M	BIM-master	0
M230	2023-03-07	16:18	31	M	BIM-master	0
F331	2023-03-07	1700	35	F	Lightindesigner student	X
F332	2023-03-07	16:28	38	F	Lightindesigner student	0
F333	2023-03-08	09:38	40	F	PhD in Lighting Science	X

Appendix 3

Consent-papers

Consent to participate in the study "Perceived brightness of colored light in comparison to white light".

We are students at the bachelor program of Lighting Design at JTH and this is a part of our thesis where we investigate perceived brightness of colored light in comparison to white light. The thesis is being executed in collaboration with Volvo Cars.

Through this study we aim to investigate whether it is possible to make guidelines for levels of colored light and thereby simplify the process of planning colored light.

The results of the study will be published in DIVA.

All information you leave is confidential and will be treated confidentially. Your name or any other personal identifying information will not be shown in any publications regarding from this study. The combination of your name and a unique code will only be available to the main researchers.

According to GDPR participants can at any time as to have their data and personal information corrected or removed from the study. To do this, contact the main researchers directly.

The experiment lasts for approximately 15 minutes and where the participants engages in visual acuity tests in light of different colors. Participants have the right to cancel at any time during the course of the experiment.

By signing this consent, you indicate that you have understood that the study is completely voluntary and how the handling of personal data will take place.

☐ I agree to participate in the study "Perceived brightness of colored light in comparison to white light".

☐ I consent to my personal data being processed in the manner explained above.

Place and date

Signature and name clarification

.....

.....

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March 2023

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Samtycke till att delta i forskningsprojektet "Perceived brightness of colored light in comparison to white light".

Vi är studenter vid kandidatprogrammet för Ljusdesign på JTH och detta är en del av vårt examensarbete där vi undersöker upplevd intensitet på färgat ljus jämfört med vitt ljus. Examensarbetet skrivs i samarbete med Volvo Cars.

Genom denna studie vill vi undersöka om det går att ta fram riktlinjer för nivåer av färgat ljus och därmed förenkla processen av projektering av färgat ljus.

Resultatet av studien kommer att publiceras på DIVA.

All information du lämnar är konfidentiell och kommer att behandlas konfidentiellt. Ditt namn eller någon annan personlig identifierande information kommer inte att visas i några publikationer som härrör från denna studie. Matchen mellan ditt namn och en unik kod kan endast nås av huvudforskaren.

I enlighet med GDPR kan deltagare när som helst be att få sina uppgifter rättade eller raderade från studien. Detta görs genom att kontakta huvudforskarna direkt.

Själva experimentet tar ca 15min och innebär att deltagaren deltar i olika syntester med olika färgat ljus. Deltagare har rätt att avbryta när som under experimentets gång.

Genom att signera detta samtycke så anger du att du har förstått att studien är helt frivillig och hur hanteringen av personuppgifter kommer att ske.

☐ Jag samtycker till att delta i studien "Perceived brightness of colored light in comparison to white light".

☐ Jag samtycker till att mina personuppgifter behandlas ovan förklarat sätt.

Plats och datum

Underskrift och namnförtydligande

.....

.....

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sofiac Linden@gmail.com

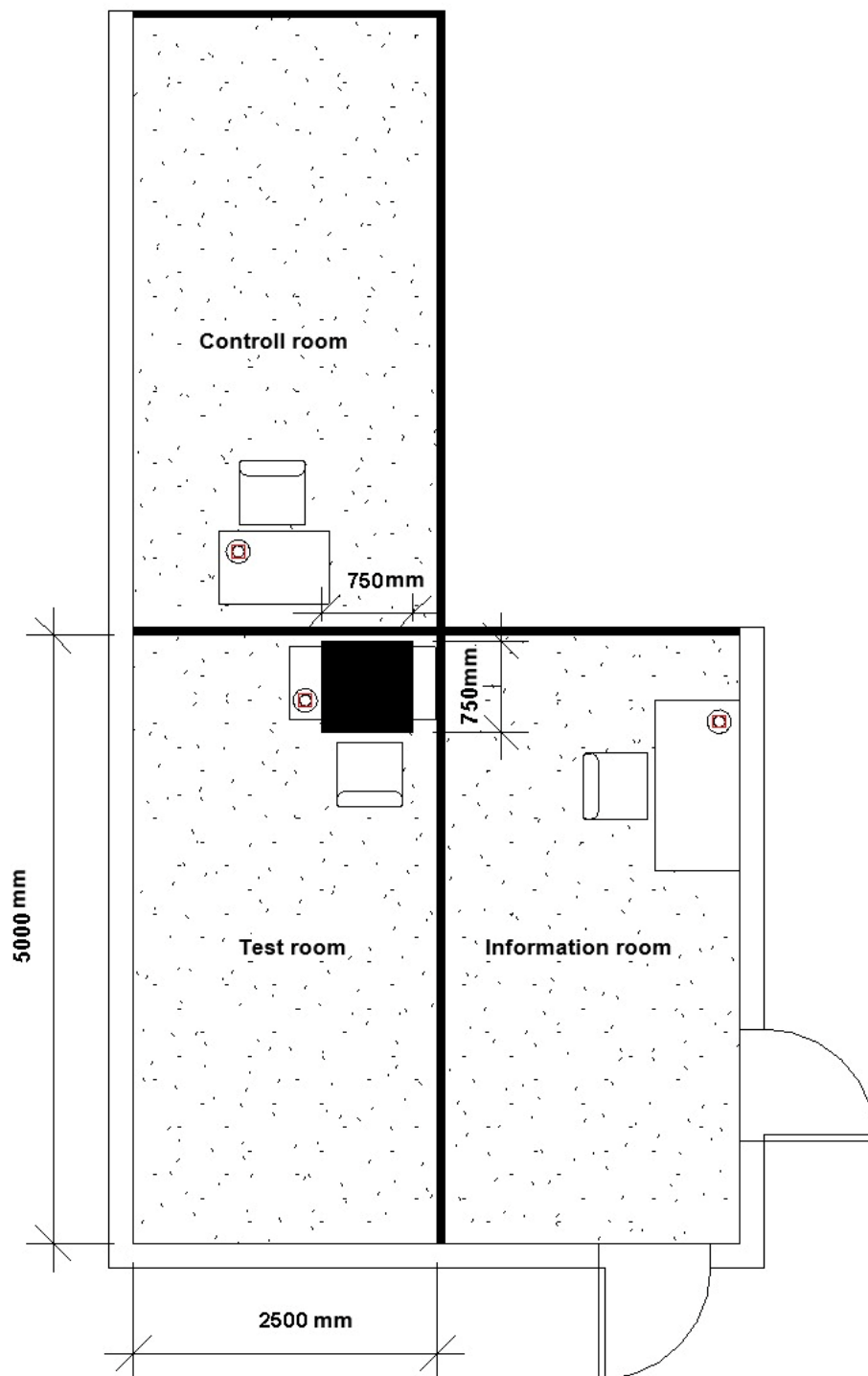
Jönköping School of Engineering
Department of Lighting Design
March 2023

Razan Albunyaha
+4621273842
razan.albunyaha85@gmail.com

Appendix 4

Room description

The following drawing shows the outline of the different rooms used in the experiment. The dividing walls are made out of black, matt, fabric with a “black-out” function. The Participants entered and exited through the door at the right. The black square represents the apparatus. The red circles represent desk luminaires.



Appendix 5

Product sheet of LED-strip



BTF-LIGHTING

深圳市糊糊蝶照明科技有限公司

---SHENZHEN BTF-LIGHTING TECHNOLOGY CO.,LTD---

Specification

规格书

Factory Model/产品型号: BTF-5V-RGBWIC-SK6812RGBNW-144L-W30

Sending Date/创建日期: 2022/4/29

Production Unit/创建单位: 深圳市糊糊蝶照明科技有限公司

Address/地址: 2F, Bld. C-C1, Chuangfu Tech Park, Beihuan Rd., Shiyan St., Baoan District, Shenzhen, Guangdong, China.

地址: 广东省深圳市宝安区石岩街道石环路创富科技园C栋2楼

Phone Number/联系电话: 86-134 1612 8074

Contact Person/联系人: Sinon-Lee

Email/电邮: contact@btf-lighting.com

Web/网址: www.btf-lighting.com

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Version History 修订履历

Date 日期	Revised content 修订内容	Version 版本	Revised by 修订人



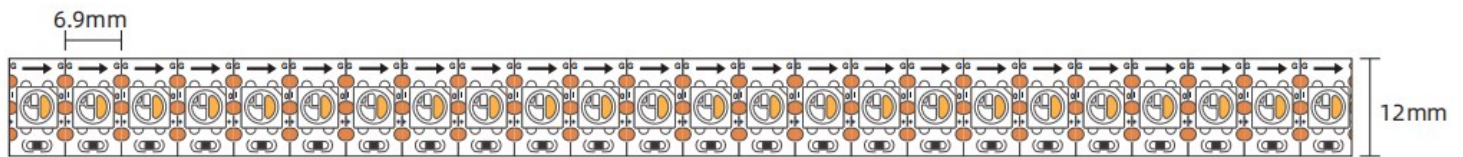
Features (特征)

1. **PRECISION SMT PROCESS** (精准贴片工艺)
2. **BUILT-IN IC** ; ONE IC DRIVES ONE LED ; RGBW 4 CHANNEL (内置IC; 单点单控; RGBW 4通道)
3. **WIDE VIEWING ANGLE** (最大120° 大角度发光)
4. **CE/RoHS/FCC/REACH COMPLIANT** (符合CE/RoHS/FCC/REACH 标准)
5. **PACKAGE:1M/REEL.** (包装每卷1米)

Application (应用)

1. **GENERAL LIGHTING** (普通照明)
2. **LINEAR LIGHTING** (线性照明)
3. **FURNITURE LIGHTING** (家具照明)
4. **DECORATIVE AND ENTERTAINMENT LIGHTING** (装饰与娱乐照明)
5. **ATMOSPHERE LIGHTING** (氛围照明)

Package Dimension 500MM ± 2MM (封装尺寸500MM ± 2MM)



Notes (备注):

1. **All dimensions are in millimeters** (所有标注尺寸单位为毫米)
2. **Tolerances are ± 0.15mm unless otherwise noted** (除特别标注外, 允许公差为±0.15mm)
3. **Customized 0.5m delivery** (可0.5m出货)

Product Number Explanation (产品编码说明)

BTF - □□□ - □□□ - □□□ - □□□ - □□□ □□□
① ② ③ ④ ⑤ ⑥ ⑦

- ① BTF (糊糊蝶公司简称缩写代码)
- ② **FORWARD VOLTAGE** (标称电压): 5V/12V/24V/36V/48V.....
- ③ **CHIP TYPE** (芯片类型): RGB/RGBW/RGBCCT/RGBIC/RGBWIC/RGBCCTIC.....
- ④ **CHIP NAME** (芯片名称): WS2812B/WS2812E/WS2813/WS2811/WS2815/3535/5050.....
- ⑤ **LED QTY** (LED数量): 18/30/60/74/96/100/144.....
- ⑥ **PCB COLOR** (灯条PCB颜色): WHITE/BLACK
- ⑦ **WATER PROOF GRADE** (防水等级): IP30/IP65/IP67/IP68

PARAMETER LIST (参数表)

PARAMETER (参数)	Color Centre (颜色)	Parameter value (参数数值)
发光亮度/IV	Red (红光)	240-450MCD
	Green (绿光)	580-1050MCD
	Blue (蓝光)	120-240MCD
	White (白光)	1800-2525MCD
主波/WD	Red (红光)	240-450NM
	Green (绿光)	580-1050NM
	Blue (蓝光)	120-240NM
	White (白光)	NM
电压/VF	Red (红光)	2.0-2.4V
	Green (绿光)	2.8-3.2V
	Blue (蓝光)	2.8-3.2V
	White (白光)	3.2-3.5V

Absolute maximum ratings per meter (每米绝对最大额定值)

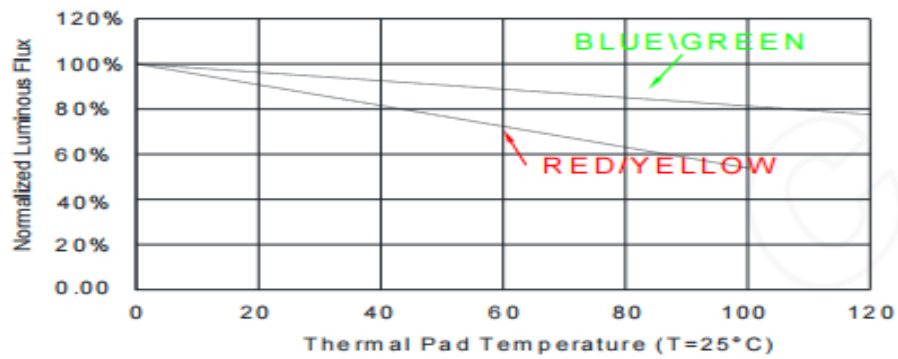
Item (项目)	Symbol (符号)	Range value (范围)	Unit (单位)
逻辑电源电压	V _{in}	3.7~5.5	V
RGB 输出端口耐压	V _{ds}	5	V
逻辑输入电压	V _I	-0.5~0.5+VDD	V
RGB 端口输出电流	I _{ol1}	8-16.5	MA
工作温度	T _{opt}	-40~85	°C
储存温度	T _{stg}	-40~85	°C
ESD 耐压	V _{esd}	2	KV

Electrical-Optical characteristics (电性与光学特性)

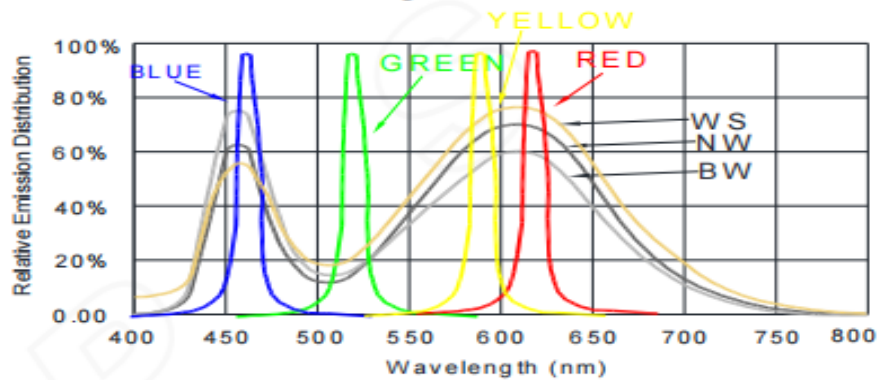
Item (项目)	Absolute Maximum Rating (数值/M)
Input Voltage (输入电压)	DC5V
Input Current (输入电流)	7.2A
Power Dissipation (功率消耗)	36W±10%
Color Rendering Index (显指)	90
View Angle (角度)	120°
Light Efficiency (光效)	N/A
LED QTY (芯片数量)	144leds/m
Cut length (剪切长度)	6.9MM

典型光学特性曲线

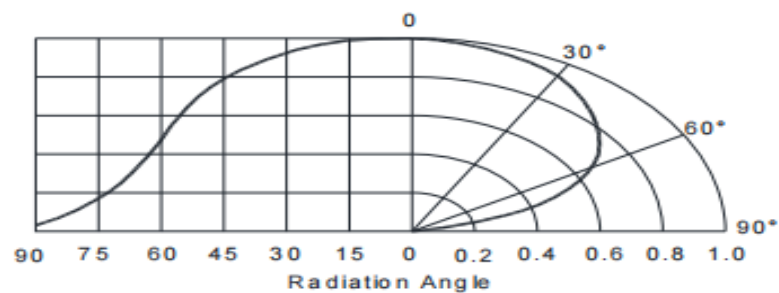
Thermal Pad Temperature vs. Relative Light Output



Wavelength Characteristics



Typical Radiation Pattern 120°





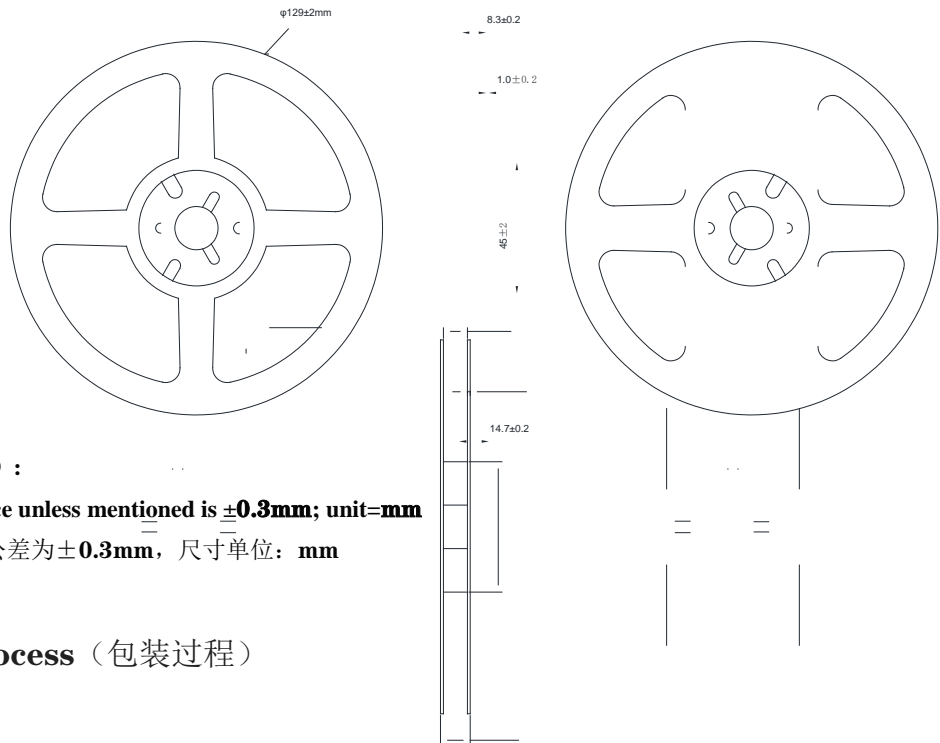
可靠性测试数据

NO.	Test item	Test Conditions	Reference	Criterion
1	Thermal Shock	$100 \pm 5^{\circ}\text{C} \sim -40^{\circ}\text{C} \pm 5^{\circ}\text{C}$ 15min~15min 100 cycles	MIL-STD-202G	0/22
2	High Temperature Storage	$T_a = +100^{\circ}\text{C}$ 1000hrs	JEITA ED-4701 200 201	0/22
3	Low Temperature Storage	$T_a = -40^{\circ}\text{C}$ 1000hrs	JEITA ED-4701 200 202	0/22
4	High Temperature High Humidity Storage	$T_a = 60^{\circ}\text{C}$ RH=90% 1000hrs	JEITA ED-4701 100 103	0/22
5	Temperature Cycle	$-40^{\circ}\text{C} \sim 25^{\circ}\text{C} \sim 100^{\circ}\text{C} \sim 25^{\circ}\text{C}$ 30min~5min~30min~5min 100 cycles	JEITA ED-4701 100 105	0/22
6	Resistance to Soldering Heat	$T_{\text{sld}} = 260^{\circ}\text{C}$, 10sec. 2 times	JEITA ED-4701 300 301	0/22
7	Room temp Life Test	25°C , IF: Typical current, 1000hrs	JESD22-A 108D	0/22

Criteria for Judging the Damage:

Item	Symbol	Test Condition	Limit	
			Min	Max
Luminous Intensity	IV	DC=5V, Typical current	Init. Value*0.7	---
Resistance to Soldering Heat	---	DC=5V, Typical current	No dead lights or obvious damage	

Reel Dimensions （卷盘尺寸）

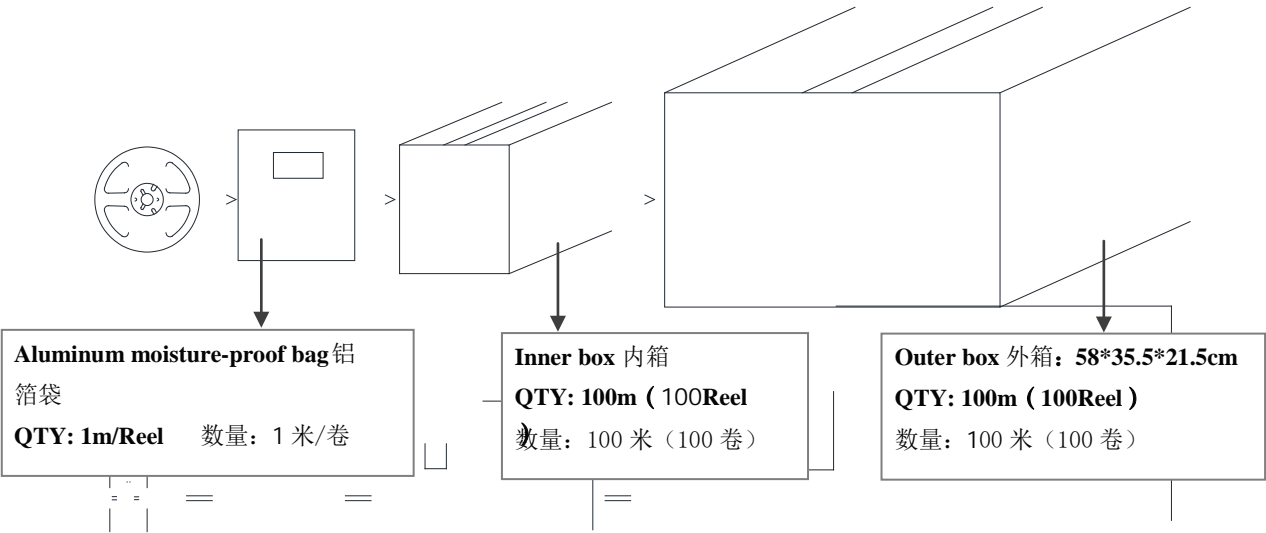


Note（备注）：


Tolerance unless mentioned is $\pm 0.3\text{mm}$; unit=mm

未标注公差为 $\pm 0.3\text{mm}$ ，尺寸单位：mm

Packing Process （包装过程）



Accessories (配件)

Model (产品名称)	Pictorial (图片)	Features (特性)	Note (备注)
3PIN-SM接头		可续接或更换SM接头	

Cautions (使用注意事项)

1. Avoid contact hard objects on the emitting area.

避免发光区接触尖硬物品。

2. Soldering iron temperature should be less than 305, single soldering time should be controlled within 3S.

焊接时烙铁温度需小于 305°，单次焊接时间控制在 3s 以内。

3. Min. Vertical Bending Length: 25cm360°, Min. Horizon Bending Length: 1cm, Max. Vertical Bending angle: 50cm720°.

最小垂直扭曲长度: 25cm, 扭曲角度 240°，最小水平扭曲直径 1cm, 最大垂直扭曲角度 50cm 角度 720°。

4. Max. Input Voltage: <110% of standard Input Voltage.

输入电压不能超过额定电压的 1.1 倍，否则会有失效风险。

Appendix 6
Landholt C-test

40

70

100

130

160

190

220

250

280

310

340

370

400

430

460

490

































520

550

580

610

640

D = 5,0									V = 1,0
D = 5,0									V = 1,0
D = 5,0									V = 1,0
D = 5,0									V = 1,0

Appendix 7

Date white light

Descriptive statistics	
Mean	6,8%
Standard Error	1,0%
Median	4,5%
Mode	4,5%
Standard Deviation	5,5%
Sample Variance	0,3%
Kurtosis	105,8%
Skewness	135,1%
Range	21,0%
Minimum	1,0%
Maximum	22,0%
Sum	2,24
Count	33

Participant	Intensity Max 255	Intensity in % Max 100%	Illuminance (x0.1) Max 200	Illuminance in % Max 100%
M201	18	7%	15	8%
M102	31	12%	24	12%
M103	32	13%	26	13%
F104	18	7%	14	7%
F105	21	8%	17	9%
F206	40	16%	32	16%
M207	9	4%	6	3%
M208	8	3%	6	3%
M109	12	5%	9	5%
F110	7	3%	5	3%
M111	12	5%	9	5%
F112	20	8%	16	8%
F213	15	6%	11	6%
M114	8	3%	6	3%
F215	6	2%	4	2%
F116	57	22%	44	22%
M217	6	2%	4	2%
F118	11	4%	9	5%
M319	12	5%	8	4%
M120	4	2%	3	2%
M221	47	18%	38	19%
F122	6	2%	4	2%
F123	19	7%	15	8%
M124	14	5%	11	6%
F125	9	4%	7	4%
F226	12	5%	9	5%
M227	5	2%	3	2%
M128	31	12%	25	13%
M129	7	3%	5	3%
M230	2	1%	2	1%
F331	14	5%	11	6%
F332	17	7%	14	7%
F333	50	20%	36	18%

Appendix 8

Date red light

Descriptive statistics	
Mean	15%
Standard Error	3%
Median	8%
Mode	8%
Standard Deviation	16%
Sample Variance	2%
Kurtosis	683%
Skewness	242%
Range	73%
Minimum	4%
Maximum	77%
Sum	504%
Count	33

Participant	Intensity Max 255	Intensity in % Max 100%	Illuminance (x0.1) Max 26	Illuminance in % Max 100%
M201	88	35%	10	38%
M102	43	17%	5	19%
M103	69	27%	8	31%
F104	38	15%	4	15%
F105	34	13%	4	15%
F206	183	72%	20	77%
M207	23	9%	2	8%
M208	10	4%	1	4%
M109	30	12%	3	12%
F110	9	4%	1	4%
M111	14	5%	1	4%
F112	32	13%	3	12%
F213	27	11%	2	8%
M114	10	4%	1	4%
F215	61	24%	6	23%
F116	86	34%	9	35%
M217	19	7%	2	8%
F118	30	12%	3	12%
M319	19	7%	2	8%
M120	12	5%	1	4%
M221	61	24%	6	23%
F122	13	5%	1	4%
F123	30	12%	3	12%
M124	21	8%	2	8%
F125	21	8%	2	8%
F226	14	5%	1	4%
M227	20	8%	2	8%
M128	21	8%	2	8%
M129	17	7%	2	8%
M230	7	3%	1	4%
F331	29	11%	3	12%
F332	50	20%	5	19%
F333	132	52%	13	50%

Appendix 9
Date green light

Descriptive statistics	
Mean	8%
Standard Error	1%
Median	5%
Mode	6%
Standard Deviation	8%
Sample Variance	1%
Kurtosis	964%
Skewness	274%
Range	40%
Minimum	1%
Maximum	42%
Sum	258%
Count	33

Participant	Intensity Max 255	Intensity in % Max 100%	Illuminance (x0.1) Max 77	Illuminance in % Max 100%
M201	36	14%	10	13%
M102	16	6%	5	6%
M103	39	15%	12	16%
F104	22	9%	6	8%
F105	20	8%	5	6%
F206	46	18%	14	18%
M207	9	4%	2	3%
M208	5	2%	1	1%
M109	15	6%	4	5%
F110	6	2%	1	1%
M111	20	8%	5	6%
F112	33	13%	10	13%
F213	14	5%	4	5%
M114	8	3%	2	3%
F215	27	11%	7	9%
F116	53	21%	16	21%
M217	8	3%	2	3%
F118	12	5%	3	4%
M319	20	8%	5	6%
M120	5	2%	1	1%
M221	45	18%	13	17%
F122	8	3%	2	3%
F123	18	7%	5	6%
M124	15	6%	4	5%
F125	13	5%	4	5%
F226	10	4%	3	4%
M227	14	5%	4	5%
M128	12	5%	3	4%
M129	11	4%	3	4%
M230	5	2%	1	1%
F331	11	4%	3	4%
F332	27	11%	7	9%
F333	116	45%	32	42%

Appendix 10
Date blue light

Descriptive statistics	
Mean	22%
Standard Error	3%
Median	15%
Mode	12%
Standard Deviation	19%
Sample Variance	4%
Kurtosis	212%
Skewness	158%
Range	79%
Minimum	3%
Maximum	82%
Sum	733%
Count	33

Participant	Intensity Max 255	Intensity in % Max 100%	Illuminance (x0.1) Max 77	Iluminance in % Max 100%
M201	82	32%	10	30%
M102	30	12%	4	12%
M103	129	51%	17	52%
F104	38	15%	5	15%
F105	79	31%	10	30%
F206	208	82%	27	82%
M207	48	19%	6	18%
M208	29	11%	4	12%
M109	93	36%	12	36%
F110	10	4%	1	3%
M111	31	12%	4	12%
F112	38	15%	5	15%
F213	45	18%	6	18%
M114	11	4%	1	3%
F215	63	25%	7	21%
F116	137	54%	17	52%
M217	40	16%	5	15%
F118	31	12%	4	12%
M319	27	11%	3	9%
M120	20	8%	2	6%
M221	156	61%	20	61%
F122	20	8%	2	6%
F123	31	12%	4	12%
M124	33	13%	4	12%
F125	51	20%	6	18%
F226	22	9%	3	9%
M227	28	11%	3	9%
M128	62	24%	7	21%
M129	39	15%	5	15%
M230	27	11%	3	9%
F331	37	15%	4	12%
F332	126	49%	16	48%
F333	132	52%	15	45%

Appendix 11

T-test

t-Test: Paired Two Sample for Means

	<i>White Illuminance in %</i>	<i>Red Illuminance in %</i>
Mean	0,068	0,153
Variance	0,003	0,025
Observations	33	33
Pearson Correlation	0,713	
Hypothesized Mean Difference	0	
df	32	
t Stat	-3,9186	
P(T<=t) one-tail	0,0002	
t Critical one-tail	1,6939	
P(T<=t) two-tail	0,0004	
t Critical two-tail	2,0369	

	<i>White Illuminance in %</i>	<i>Green Illuminance in %</i>
Mean	0,068	0,078
Variance	0,003	0,006
Observations	33	33
Pearson Correlation	0,783	
Hypothesized Mean Difference	0	
df	32	
t Stat	-1,203	
P(T<=t) one-tail	0,119	
t Critical one-tail	1,694	
P(T<=t) two-tail	0,238	
t Critical two-tail	2,037	

	<i>White Illuminance in %</i>	<i>Blue Illuminance in %</i>
Mean	0,068	0,222
Variance	0,003	0,035
Observations	33	33,000
Pearson Correlation	0,775	
Hypothesized Mean Difference	0,000	
df	32,000	
t Stat	-5,969	
P(T<=t) one-tail	0,000	
t Critical one-tail	1,694	
P(T<=t) two-tail	0,000001	
t Critical two-tail	2,037	