Visibility of color over angle for Gaussian luminance profiles

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Visibility of Color over Angle for Gaussian Luminance Profiles

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This report will describe my graduation project at Human Technology Interaction group in Department of Industrial Engineering and Innovation Sciences of Eindhoven University of Technology, The Netherlands. My keen interest to quantify our visual perception led me to gain further knowledge on its practical applicability along with the theoretical learnings. I had a very pleasant and informative internship at Philips Lighting Research, Eindhoven under solid supervision of associated research scientists. Basically I had to analyze a specific problem related to the physics of light and find out solutions from the point of view of human vision to counter that problem efficiently and cost-effectively. This hints to a multidisciplinary platform to solve a problem where knowledge on psychology, technology, optics, signals, statistics etc. are required. This made this entire study challenging and exciting simultaneously.

I consider this study as a small but significant contribution towards the large innovation in LED lighting system which is the future to solve problems related to the ensuing energy crisis around the world. Although I am now more aware of the fact that there are still a lot of blanks to be filled in and follow up research are needed, I am confident that we are making good progress in minimizing the existing faults of LED lights which will make people convinced to shift to LED gradually for a better future. I really enjoyed working on this project and was able to get a proper taste of what it means to do explorative research and having to develop and evaluate novel research directions and techniques.

I would like to thank my supervisors from Philips lighting research, Dr. ir. Marc Lambooij and Dr. ir. Marcel Lucassen, and supervisors from Eindhoven University of technology, Dr. ir. Ingrid Vogels and Dr. ir. Raymond Cuijpers for their valuable insights on the topic along with expert guidance, feedback and support. I would also like to thank few colleagues in Lighting Experiences group in Philips Lighting Research, Dr. Dragan Sekulovski, Ruud Baselmans, Gosia Perz for their selfless help and support in setting up the experiment, and developing the needed computer programs. Also, many thanks to the co-interns in Philips Research for brainstorming problems and enjoying together to turn the internship into an amazing experience. Last but not the least, I would also like to thank my family for their constant and unconditional support to achieve this.

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ABSTRACT

In spite being one of the advanced and highly efficient technological advancements in the lighting industry, LEDs have difficulties in creating color uniform light. This study aims to investigate one kind of spatial color non-uniformity problem exists in a LED spot, called the color-over-angle (CoA) effect, being a (gradual) change in chromaticity from center to the edge of the spot. Instead of incorporating an expensive specially designed optics to mitigate these problems, a more cost effective solution is to find the visibility thresholds, where we do not perceive any difference even if there is a physical difference in color, and that is the topic of the focus in this research.

For a standard Gaussian function as realistic luminance profile of a LED spot, the visibility threshold of a CoA effect is a function of several lighting parameters, such as the peak luminance level, the width of the luminance profile, the steepness and the position of the chromaticity transition in the spot. While comparing at constant absolute luminance level in a spot, people perceive the CoA effect similarly even if the peak luminance level is changed. But at constant relative luminance in the same spot where only absolute luminance changes, the lower peak luminance value makes the CoA effect significantly less detected which supports the finding by Kim et al. (2013). Also, the closer a color transition occurs towards the center of the spot, the more easily the CoA effect is detected. These indicate that the local absolute luminance value is a better crucial factor in changing the visibility than the relative luminance values in the spot. In addition, a wider luminance profile makes the CoA effect significantly less visible. Furthermore, a smooth color transition draws effectively more visibility thresholds which is in line with Vogels & Lambooij (2014). Also, a methodological research is performed to investigate how differently we evaluate LED spots in presence or absence of a reference ‘ideal’ spot. The visibility of a CoA in a spot is found more easily detected (almost by a factor of 2), when a comparison is made with a reference spot presented simultaneously, which backs the findings by Rosenberger et al. (2012). Several possibilities of the relevant future research are also discussed accordingly.

Keywords: LED spot, color over angle, visibility threshold, Gaussian luminance, color transition, size of luminance profile, relative luminance, methodological research
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INTRODUCTION

Research revealed that lighting alone consumes about 20% of the electricity produced worldwide. It might be because of extensive usage of conventional incandescent and halogen lights still in many countries with large population which consume a good amount of energy every year. Hence, world leaders are trying to replace the traditional lighting technology with a more energy efficient and cost effective way. In the last decade, compact fluorescent lights (CFL) was thought of as a game changer which saves more energy than incandescent bulbs. Of late, light emitting diode (LED) technology is in practice to compete with CFL in terms of many advantages. LED not only offers many opportunities to create radically new luminaire designs at substantial lower cost and reduced environmental impact but also competes in efficient light output (lumen/Watt) with same energy input as CFL. Apart from that, LEDs produce very little heat in comparison to incandescent and CFL which release around 90% and 80% of their energy as heat respectively. Frances Saunders, president of Britain’s Institute of Physics said: “With 20 percent of the world’s electricity used for lighting, it’s been calculated that optimal use of LED lighting could reduce this to 4 percent” (Reuters-UK, 2014). LEDs are now being used in applications such as household and office lighting, traffic signals, aviation lighting, automotive headlamps etc. LED is a two-lead semiconductor light source. It is a p-n junction diode, which emits light when activated. When a suitable voltage is applied to the leads, electrons (-ve charged) are able to recombine with electron holes (+ve charged) within the device, releasing energy in the form of photons. The color of the light is determined by the energy band gap of the semiconductor (Schubert, 1998). Hence, we can get a full control of the color and better usage of hue produced by LEDs by choosing the right material. Besides, LEDs can accommodate a faster temporal response to the changes in the driving signal. They can also be controlled using internet from a long distance as the chip inside them can be programmed and assigned with an IP address which make LEDs as a new dimension in lighting technology in many aspects.

In spite of having so many advantages, still some problems exist during LED manufacturing and assembling, such as color non-uniformity, color-over-angle effect etc. These problems can be mitigated by using specially designed optics which are an expensive procedure. A more cost effective way to deal with these issues can be addressed from human visual point of view and find solutions accordingly, which are discussed in following sections. But before that, some background knowledge is also presented which is required to understand the problems clearly.

1.1 BACKGROUND KNOWLEDGE

1.1.1 HUMAN VISUAL SYSTEM

In the human visual system, the eye receives physical stimuli in the form of light and sends electrical signals to the brain, which interprets the signals as meaningful images. The system requires communication between its major sensory organ (the eye), and the core of the central nervous system (the brain) for processing of the external stimuli. All vision is based on the perception of electromagnetic rays. These rays pass through a transparent membrane of the human eye, called cornea, in the form of light; the cornea focuses the rays as they enter the eye through the pupil, the aperture at the front of the eye. The pupil’s size vary with the amount of light coming through the eye. The lens then focuses the incoming light rays onto the photosensitive retina in the back of the eye. The fovea is the central point of focus on the retina where we have the best spatial and color vision. Visual reception occurs at the retina where several photoreceptor cells called cones and rods are excited based on the wavelengths of incoming light to produce neural impulses which are transferred through the optic nerve to the rest of the brain for processing.

The retina of each eye contains over 100 million photoreceptor cells, responsible for converting light energy into neural activity (transduction). Human photoreceptors fall into two classes, called rods and cones on the basis of the shape of their outer segments. They differ in several important respects, such as:
they contain different light-sensitive pigments. Rods are very sensitive to low luminance levels (less than 3 cd/m²) while cones serve vision at luminance levels of greater than 0.001 cd/m² (Barber & Stockman, 2010). Thus the transition from rod to cone vision is one mechanism that allows our visual system to function over a large range of luminance levels. At high luminance levels (e.g., greater than 3 cd/m²), the rods are effectively saturated and only the cones function (Fairchild, 2013). Vision when only rods are active is referred to as scotopic vision. Vision served only by cones is referred to as photopic vision, and the term mesopic vision is used to refer to vision in which both rods and cones are active at intermediate luminance levels.

There are far more rods (around 120 millions) than cones (around 6-7 millions) present in each eye. They are not equally distributed over retina such as in fovea no rods are available whereas in periphery more rods are than cones. However, the enormous density of cones at fovea permits to visual examination of even small details of incoming lights.

There is only one type of rod present which makes it incapable of color vision. Unlike rods, there are three types of cones that differ in the photopigments they contain. Each of these photopigments has a different sensitivity to light of different wavelengths, and for this reason are referred to as ‘blue’, ‘green’ and ‘red’ or more appropriately, short (S), medium (M) and long (L) wavelength cones. This nomenclature implies that the individual cones provide color information for the wavelength of light that excites them the most. Figure 1.1 shows the spectral sensitivity curves of three cone types as well as rods. The actual sensitivities of the three cone types are shown normalized with respect to the sensitivity of rods. Another important feature about the three cone types is their relative distribution in the retina. It turns out that the S-cones are relatively sparsely populated throughout the retina and completely absent in the most central area of the fovea. The relative populations of the L : M : S cones are approximately 40 : 20 : 1 (Fairchild, 2013).

Figure 1.1 spectral sensitivity of rods and 3 types of cones; L (red) cones are most sensitive to the higher wavelength (559 nm), M cones (green) are most sensitive to high wavelength (531 nm) as well. But S (blue) cones are most sensitivity to relatively low wavelength region (419 nm). R curve is for rods which shows maximum sensitivities to the higher wavelength of colors than S cones but lesser than that of other cones (L & M).

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1 http://www.ncbi.nlm.nih.gov/books/NBK11059/
Radiometry is the science of measuring light in any portion of the electromagnetic spectrum whereas photometry is the measurement of electromagnetic radiation weighted by the human eye’s response. The latter is developed to express the amount of visible light (380-700 nm in that spectrum) in perceptual quantities by calculating the power of the light at each wavelength and weighing it with the sensitivity of the eye at that wavelength (Barati, 2012).

Figure 1.2 shows the CIE spectral luminous efficiency function (1924), for photopic vision ($V(\lambda)$) and scotopic vision ($V'(\lambda)$). This indicates that the visual system is more sensitive (with respect to the perception of brightness) to wavelengths in the middle of the spectrum and becomes less and less sensitive to wavelengths near the extremes of the visual spectrum. Even though the cone responsivities were unavailable at that time, if the cone functions are weighted roughly according to their relative population in the retina and summed, the overall responsivity matches the CIE 1924 $V(\lambda)$ function (Fairchild, 2013). This signifies that the photopic luminous response represents a combination of cone signals. The use of a spectral weighting function to predict luminance matches is the first step towards a system of colorimetry.

Besides, radiometry uses several units and quantities to describe different aspects of the entire spectrum whereas the photometry only focuses on the aspects of visible light. They are described in Table 1.1 and Figure 1.3.

**Table 1.1** Definitions and difference between radiometric and photometric units

<table>
<thead>
<tr>
<th>Radiometric units</th>
<th>Photometric units</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Radiant power</strong> (W): Energy of electromagnetic radiation emitted per unit time; expressed in Watt</td>
<td><strong>Luminous flux</strong> (lm): Measure of power of the light source in Lumen.</td>
</tr>
<tr>
<td><strong>Radiant intensity</strong> (W/sr): Measure of radiant power per unit solid angle, expressed in Watt/steradian</td>
<td><strong>Luminous intensity</strong> (lm/sr): Measure of luminous flux in a given direction, expressed in candela.</td>
</tr>
<tr>
<td><strong>Irradiance</strong> (W/m²): Radiant power received by a surface per unit area, expressed in Watt/meter²</td>
<td><strong>Illuminance</strong> (lm/m²): Total luminous flux on a surface per area, expressed in lux</td>
</tr>
<tr>
<td><strong>Radiance</strong>: Measure of radiant intensity per area of a surface, expressed in W. sr⁻¹. m⁻²</td>
<td><strong>Luminance</strong> (cd/m²): Measure of luminous intensity per area of a surface</td>
</tr>
</tbody>
</table>
Hence the luminance is an indicator of how bright the surface will appear. It is also to be noted that brightness is an attribute of visual perception whereas luminance is a physically derived parameter (radiant power weighted by the luminous efficiency function).

1.1.3 COLOR MATCHING

Following the establishment of the CIE 1924 luminous efficiency function, $V(\lambda)$, attention was turned to development of a system of colorimetry that could be used to specify when two metameric\(^2\) stimuli match in color for an average observer.

Since the cone responsivities were unavailable at that time, a system of colorimetry was constructed based on the principles of trichromacy and Grassmann’s laws of additive color mixture. The concept of this system is that color matches can be specified in terms of the amounts of three additive primaries (Red, Green and Blue) required to visually match a stimulus. This is illustrated in the equivalence statement of Equation 1.1.

$$C \equiv r^*R + g^*G + b^*B$$ (1.1)

The above Equation reads that a color $C$ is matched by $r$ units of the R primary, $g$ units of the G primary, and $b$ units of the B primary. The terms, RGB, indicate the amounts of the primaries required to match the color and are known as tristimulus values.

The next step in the derivation of colorimetry was the extension of tristimulus values such that they can be obtained for any given stimulus, defined by a spectral power distribution. However, the main disadvantage of this specification of color matching was that sometimes a negative amount of a primary color needed to be added to in order to match a monochromatic stimulus of a particular wavelength. This is because that wavelength is too saturated to be matched by the particular primaries. Clearly, a negative amount of light cannot be added to a match. Negative tristimulus values are obtained by adding the primary to the monochromatic light to desaturate it and bring it within the gamut of the primaries. For example, a 500 nm stimulus mixed with a given amount of the R primary is matched by an additive mixture of appropriate amounts of the G and B primaries.

In order to eliminate the problem of dealing with negative values addition during color matching and to force one of the color matching functions to be equal to the CIE 1924 photopic luminous efficiency function, $V(\lambda)$ (Fairchild, 2013), The CIE (International Commission on Illumination) developed (in 1931) a transformation of RGB to a new set of primaries i.e. XYZ. The negative values were removed by selecting primaries that could be

---

\(^2\) Colors that match each other even if there is a difference in their spectral power distribution
used to match all physically realizable color stimuli. This could only be accomplished with ‘imaginary’ primaries that are more saturated than monochromatic lights. Forcing one of the color matching functions to equal the V(λ) function served the purpose of incorporating the CIE system of photometry (established in 1924) into the CIE system of colorimetry (established in 1931). This was accomplished by choosing two of the imaginary primaries, X and Z, such that they produce no luminance response, leaving all of the luminance response in the third primary, Y. Figure 1.4 shows the difference between spectral tristimulus values of the CIE RBG and CIE XYZ system of colorimetry.

Figure 1.4 (left) Spectral tristimulus values for CIE RGB with monochromatic primaries at 435.8, 545.1 and 700 nm; (right) Spectral tristimulus values for CIE 1931 XYZ; the color-matching function of CIE XYZ is always positive (Fairchild, 2013).

1.1.4 CHROMATICITY DIAGRAM

We have already seen that the color of a stimulus can be specified by a triplet of tristimulus values such as in CIE 1931 XYZ color space. However, they are imaginary which signifies that this color model represents color matching functions for even physically non-existing light beams.

So, the CIE XYZ color space is an additive color space. As we have seen, it revolves around the concept of describing a color by stating the amounts of three primaries that need to be combined to make light of that color. Another important type of color space is the luminance-chromaticity color space. This relates more directly to the accurate human sensitivities on color than the additive spaces. In a luminance-chromaticity color space e.g. CIE 1931 xyY, one coordinate represents the luminance of the color (Y), while the other two, together, represent the chromaticity (x and y). All colors in the visible spectrum (380-700 nm) are represented in the chromaticity diagram using coordinate values (x,y) such that:

\[
x = X / (X + Y + Z) \\
y = Y / (X + Y + Z)
\]

(1.2) (1.3)

A third coordinate, z, could also be defined but is redundant since x+y+z = 1 for all colors. For example, (x,y) = (0.73, 0.27), (0.01, 0.75) and (0.11, 0.09) represent monochromatic red, green and blue respectively.

A chromaticity diagram provides a convenient two-dimensional representation of colors (Figure 1.5) whereas color is a three-dimensional phenomenon. The third dimension missing in the diagram is luminance.

However, chromaticity coordinates alone provide no accurate information about the color appearance of stimuli since they do not include luminance information and they do not account for chromatic adaptation as well. As an observer’s state of adaptation changes, the color corresponding to a given set of chromaticity coordinates can change in appearance dramatically (Fairchild, 2013).
1.1.5 (UNIFORM) COLOR SPACE MODEL

Most industrial standards on color uniformity, such as ANSI C78.377-2011 and Energy Star, are based on research of MacAdam (1942). In his experiment, a trained observer who was adapted to a color temperature (section 1.1.6) of 6500 K (hereafter called base color) and a luminance of 48 cd/m² were asked to match a color patch with another fixed color patch, until there was no perceived chromatic difference between the two patches. MacAdam measured the standard deviation of color matching as a function of base color (one of the 25 points on the chromaticity diagram) and color direction (the direction in which color the base color deviated). This resulted in 25 ellipses plotted in the CIE 1931 xy color space which is shown in Figure 1.6. The research of MacAdam aimed to find out the region on the chromaticity diagram that contains all colors which are indistinguishable to the color at the center of observation, or in other words, they are perceptually uniform to the base color. That means, all colors within a given ellipse are ‘perceptually’ equal to the color represented by the center of the ellipse.

In the earlier section, we discussed about the shortcomings of 1931 CIE xy diagram with respect to the correct color appearance of the stimuli. Much effort has been expended in attempts to make chromaticity diagrams more perceptually uniform. Based on MacAdam’s results, the CIE Yuv (1960) or “UCS” (uniform chromaticity scale) color space was designed, which creates a perceptually more uniform color space than the CIE xy color space (Narendran et al., 2004). However, the luminance (Y) was kept unchanged from CIE 1931 xy. The difference in non-uniformity was reduced considerably, but not enough. The (u,v) coordinates are:

\[
\begin{align*}
u &= \frac{2x}{6y - x + 1.5} \\
v &= \frac{3y}{6y - x + 1.5}
\end{align*}
\]

To further reduce the non-uniformity in color difference, another transformation of CIE 1960 UCS i.e. CIE Yu’V’ (1976) was introduced where Y remained unchanged (Ford et al., 1998). The (u’v’) coordinates are:

\[
\begin{align*}
u' &= \frac{2x}{6y - x + 1.5} \\
v' &= \frac{4.5y}{6y - x + 1.5}
\end{align*}
\]

CIE L*a*b* color space model is also widely used to attain more perceptually equal space. This means that the Euclidian distance between two color points in the color space is strongly correlated with the human visual perception.
While the chromaticity coordinates of a true blackbody source must (by definition) fall exactly on the Planckian locus, the chromaticity coordinates for an LED of a certain correlated color temperature (CCT) can fall anywhere along an iso-thermal line that intersects the blackbody locus at the equivalent color temperature. In reality, a light source with a certain correlated color temperature can have chromaticity coordinates which might significantly deviate from the blackbody source. By convention, color difference between two colors is the distance between them in a color space model.

Color difference is traditionally indicated in units of \( \Delta u'v' \). This concept of distance has evolved to become \( \Delta E \), which continues to be used today (e.g. in color spaces such as CIE L*a*b* etc.).

The color difference (\( \Delta u'v' \)) between two color points having chromaticity coordinates \((u_1', v_1')\) & \((u_2', v_2')\) in 1976 CIE u'v' color space, measured using Euclidian distance is:

\[
\Delta u'v' = \sqrt{(u_1' - u_2')^2 + (v_1' - v_2')^2}
\]

(1.8)

However, the third dimension i.e. luminance \((Y)\) is not considered in the above distance measurement as the luminance difference between those color points should be negligible as per the definition by CIE Publication 15:2004 that allows \( \Delta Y < 0.5 \) (Schanda, 2007).

1.1.6 ILLUMINANTS

Color is the visual perceptual property which derives from the spectrum of light interacting in the eye with the spectral sensitivities of the light receptors. Without light, we cannot see color. Most light sources emit light at many different wavelengths comprising a source’s spectrum, a distribution giving the intensity at each wavelength. Hence, the color of an object may appear differently under lights with different spectral distributions. An apple, for example, may appear redder under incandescent light than it would under natural daylight.

A special type of light source, known as a black-body radiator, or Planckian radiator, emits energy due to thermal excitation and it is a perfect emitter of energy. The energy emitted by a black body increases in quantity and shifts toward shorter wavelengths as the temperature of the black body increases. The spectral power distribution of a black body radiator is only determined by its absolute temperature. The temperature of a black body is referred to as its color temperature (CT) since it uniquely specifies the color (actually the spectral power distribution) of the source.

However, CT is a useful quantity as long as the chromaticity \((x,y)\) is on the black body line. White light can also be expressed in CT. However, a second quantity, correlated color temperature (CCT), is more useful if the \((x,y)\) is not on the black body line. A light source need not be a black-body radiator in order to be assigned a CCT. The CCT of a light source is simply the CT of a black-body radiator that has most nearly the same color as the source in question, measured in Kelvin (K). For example, not all white light is the same so CCT is used to differentiate the ‘shades’ of white. Higher CTS correspond to cooler white light (bluish) whereas lower CTS correspond to warmer white light (reddish). However, the CCT designation for a light source gives a good indication of the lamp’s general appearance as long as it does not deviate too much from black body line (<0.005 u’v’) (Schanda, 2007), but does not give information on its specific spectral power distribution. In Figure 1.7, the black colored parabolic line is the Planckian locus or black body locus, which is the path that the color of the black body would follow as its temperature changes. The lines perpendicular to the black body locus are the iso-thermal or iso-CCT where the color temperature is exactly same as the temperature at their interaction point on the Planckian locus.
When standardizing color appearance of objects, illuminants are used, which are not physical light sources but representations of a light’s spectral power distribution. CIE has defined several illuminants to represent certain light sources based on some certain CCTs such as standard illuminant D65 (average daylight with CCT=6500K), standard illuminant C (average daylight with CCT = 6774K), standard illuminant A (incandescent light with CCT = 2856K) etc. which are shown in Figure 1.8.

**Figure 1.7** Planckian locus and iso-thermal lines in CIE 1976 u’v’3, T_c(K) represents color temperature in Kelvin (e.g. 10000K, 6000K etc.)

**Figure 1.8** Standard illuminants (D65, D55, D50, C, E and A) in CIE uv (1960) color space

### 1.1.7 LED BINNING

LEDs are manufactured in millions at a time using high-speed processes. Just like any other natural growth process such as crystals, diamonds, plants, or even people, no two LEDs are alike. LED components usually differ from each other during production even with slightly variations in factors such as CCT, lumen output and forward voltage (Schneiker, 2004). In the solid state lighting (SSL) field, stable and homogenous light from products is extremely important. Needless to say that human eyes can discern differences in color extremely well. Hence,

3 http://lumenhub.com/color-and-cct/
4 http://en.academic.ru/dic.nsf/enwiki/4059
Manufacturers opted for a technique to classify or sort the produced LEDs into similar categories, or bins based on their similarity on the factors (CCT, lumen and voltage) mentioned above. This process is called LED binning. Among those factors, the best known parameter in LED binning — is LED color as typically measured in CCT. Color temperature bins are defined by (x,y) coordinates on the CIE 1931 chromaticity diagram. These bins are grouped as quadrants around the iso-thermal lines for a specified color temperature as shown in Figure 1.9. The larger the bin size, the more variation around the standard color temperature is. Conversely, smaller bin sizes maintain a tighter control of color variation.

![Figure 1.9](http://www.ledlightsydney.com/binning.html)

However, due to the variable nature of the color produced by white light LEDs, a convenient metric for expressing the extent of the color difference within a batch (or bin) of LEDs is the number of SDCM (standard deviation color matching) ellipses steps in the CIE color space that the LEDs fall into. For example, if the chromaticity coordinates of a set of LEDs all fall within 1 SDCM (or a “1-step MacAdam ellipse”), most people would fail to see any difference in color. But one might start to see some color difference as the variation in chromaticity extends to a zone that is twice as big (2 SDCM or a 2-step MacAdam ellipse). A 2-step MacAdam ellipse is better than a 3-step zone, and so on. However, most LEDs are binned within the 4-7 step MacAdam ellipses.

### 1.2 PROBLEM SPECIFICATION

#### 1.2.1 COLOR NON-UNIFORMITY

Though LEDs are one of the advanced and highly efficient technological advancements in the lighting industry, they have difficulties in creating color uniform light as manufacturing processes produce LEDs that vary greatly in either the amount of light produced (lumen) or in the color content. In practice this means that non-uniformities can be noticed even if LEDs that come from the same bin are excited with same amount of current. Figure 1.10 shows a typical problem with LED luminaires displayed in showrooms in which color non-uniformity is clearly seen at the wall. This kind of problems can also be seen with aging of LEDs as LEDs get slightly dimmer as they are used and the proportion of getting dim is not equal for all LEDs used any light applications.

However, a tighter LED binning (for example, sorting the bins according to lumen output and color with less than 2-step MacAdam ellipses) during manufacturing could resolve the color non-uniformity issue to some extent but that will be expensive as binning is a time consuming and costly process. Also, within a luminaire, special optics may mix the light of individual LEDs to make the color variation unperceivable. However, color differences can still be perceived between luminaires with the same color specs. Several lighting parameters affect the visibility
of color non-uniformity in a lighting application, which will be discussed later along with relevant research outcomes.

![Figure 1.10 Color non-uniformity in luminaires in showroom](https://www.linkedin.com/pulse/white-led-color-temperature-difference-easy-guide-how-floroiu)

Whenever we say that color non-uniformity exists in any lighting application, it signifies that more than one color can be visible in that application. Since, we used CIE 1976 u’v’ color space model for our experimental stimuli creation, which is a small improvement over CIE 1960 uv, we will limit our discussion about color difference in this color space model only.

### 1.2.2 COLOR OVER ANGLE

In practice, LED spot lights have a specific kind of color non-uniformities called Color over Angle (CoA), being a (gradual) change in chromaticity from center to the edge of the spot. Figure 1.11 shows a typical CoA artefact of a LED spot light projected on wall. White light can be formed by different LED technologies. The two principles possibilities are the combination of LEDs with different bandwidths (mixed color), or the conversion of blue light with (remote) phosphors (Steigerwald et al., 2002). According to Optoelectronics Industry Development Association (2001), mixed-color LEDs are expected to have greater luminous efficacy because they do not undergo down-conversion losses like phosphor-converted white LEDs. However, the light of different spatially separated colored LED chips has to be mixed which create color non-uniformities and for that, it requires additional optical elements to reduce spatial color variations and create uniform white light. This raises the cost again. To avoid this problem, remote phosphor method could be adopted as an alternative and efficient method to create white light. This type of LED consists of a blue LED chip with on top a so-called phosphor layer which converts part of the blue light into yellow and red (Figure 1.12). The resulting output is white light. However, this too has a serious problem as paths of the rays through the phosphor at different angles are of different length, resulting in different amounts of the blue light being converted. This is often visible in the form of a yellow ring which is shown in Figure 1.13. This is the problem of Color over Angle (CoA) variation.

![Figure 1.11 CoA artefacts in LED spot light](http://glassbox-design.com/2010/acropora-coral-grow-led-aquarium/)

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6 [https://www.linkedin.com/pulse/white-led-color-temperature-difference-easy-guide-how-floroiu](https://www.linkedin.com/pulse/white-led-color-temperature-difference-easy-guide-how-floroiu)

To avoid CoA issue, several innovative technologies have been researched and developed (e.g. diffuser layers, scattering elements, facets, micro-lenses, collimators etc.) (Mueller et al., 2008; Wang et al., 2010; Prins et al. 2014). Yet these methods reduce the efficiency of the LED and increase the production cost. Hence, in real applications, one needs to understand the perception of spatial color differences in order to determine the allowed variation in chromaticity of LED spot lights which seems to be more cost effective (than using expensive special optics) and efficient way of dealing with problems such as color non-uniformity and color-over-angle effect.

1.3 DIFFERENT WAYS OF EVALUATING THE QUALITY OF LED SPOTS

In practical scenario, the LED spots can be evaluated in two different ways such as looking at the spot light projected on the wall along with another spot (a reference) which is considered to be producing the ‘perfect’ light with minimal color non-uniformity or color-over-angle effect. And the other one is just to looking at the LED spot light without comparing to any such reference light. The latter accounts for a subjective evaluation which can also be differed by individual experiences. In experimental research, several psychophysical methods (section 1.4.1) are generally used to measure the visibility thresholds for both the above mentioned cases. However, in spite of using few effective psychophysical procedures like staircases (section 1.4.2) etc. to measure the thresholds, still they tend to differ in how they are evaluated. For example, visibility thresholds measured in a spot with color non-uniformity by comparing it to a reference where ‘no’ color non-uniformity exists tends to result in lower thresholds than measuring the same without comparing to any reference. Sometimes, the thresholds for latter deviates from that of the former even with a factor of 2 (Rosenberger et al., 2012). However, in reality, the latter resembles more to the practical applications where users are only shown with the light projected on the wall before buying.

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8 http://www.ledinside.com/knowledge/2015/8/color_consistency_one_of_the_challenges_for_solid_state_lighting
1.4 PROCEDURES TO MEASURE VISIBILITY THRESHOLD

1.4.1 PSYCHOPHYSICAL EXPERIMENTS

Psychophysics is the scientific study of the relationships between the physical measurements of stimuli and the sensations and perceptions that those stimuli evoke. The tools of psychophysics are used to derive quantitative measurements of perceptual phenomena that are often considered subjective (Fairchild, 2013).

There are few methods used to measure the threshold of a stimulus, such as:

1) *Method of adjustment (tuning)*: The observer controls the stimulus magnitude and adjusts it to a point that is just perceptible (absolute threshold) or just perceptibly different (difference threshold) from a starting level.

2) *Method of limits*: The stimuli are presented in either ascending (imperceptible to just noticeable) or descending (perceptible to just unnoticeable) series. The threshold is taken to be the average of both of them.

3) *Method of constant stimuli*: The experimenter chooses several stimulus intensity levels around the level of the threshold. Then each of these stimuli is presented multiple times in random order. Over the trials, the frequency with which each stimulus level is perceived is determined.

The above methods however are not stable as they are prone to biases. The method of constant stimuli is improved over years into very efficient and stable procedures, among which staircase method is extensively used nowadays.

1.4.2 STAIRCASE METHOD

Staircase method, or the method of up and down, is one of advanced adaptive techniques under method of constant stimuli (Fairchild, 2013) which has come into extensive use in the last few years. It is an efficient psychophysical procedure that has been discussed in detail by Dixon & Massey (1957) and Cornsweet (1962).

Staircases usually begin with a high intensity stimulus, which is easy to detect. A stimulus is presented and the observer is asked to respond. If the response is correct, the same or decreased stimulus intensity is presented again. But if the response is incorrect, the stimulus intensity is increased for the next trial. Whenever a transition happens between “correct” and “incorrect”, the direction of stimuli sequence is reversed. The transition points are called breakpoints. The threshold values are finally calculated as average of the stimuli values at a definite number of breakpoints. Experimental variables that may impact the results of the methodology include the amount of difference between stimulus values presented (the step size), the initial starting value of the stimulus, the process that guides the sequence of presentation levels on each trial (the tracking algorithm), and the decision for ending the process (the stopping rule). The general goal of each procedure is to measure characteristics of the subject’s performance over the shortest amount of time, without sacrificing accuracy (Leek, 2001).

Although a normal up and down staircase targets 50% performance level, changing in the weightage of up-and-down can alter the percentage of the correct responses. For example, Levitt (1971) found that a 1-down/2-up staircase method can achieve 70.7% of correct responses in the psychometric curve. Later, Kaernbach (1991) described that 75% of correct performance can be achieved with a ratio of up and down step sizes as a factor of 3. For example, a one-down/three-up staircase method in which stimulus level is changed upward after an incorrect response and downward after a correct response, and the size of the upward step should be three
times the size of the downward step converges to 75% correct responses. Figure 1.14 explains this with an example taken from the data of one participant in our experiment for a clear demonstration.

Figure 1.14 A 1-down/3-up Staircase method with stimulus intensity in y-axis and the number of trials in x-axis. It starts with a higher stimulus intensity. Correct answer decreases the distance from thresholds by 1 and incorrect answer increases that by factor of 3 of the previous decrement size. So the step size is dynamic after each reversal. The experiment is repeated until 8 such reversals and takes average thresholds of the last 4 reversals.
2 LITERATURE OVERVIEW

So far, we have discussed two specific problems (color non-uniformity and color-over-angle) seen in LEDs where there is always a tradeoff between the quality of the light and the cost in any application. It seems to be more cost effective and efficient to deal with these problems if some variations are allowed in the chromaticity of LEDs so that people do not perceive any color difference, even if there is a physical difference in color. In order to achieve that successfully, one needs to understand the perception of spatial color differences (see for example, Vogels et al., 2014).

Spatial vision relies fundamentally in the detection of spatial features in the visual stimulus. The spatial resolution of the visual system was initially assessed using a simple measure of static visual acuity, which commonly refers to the clarity of vision (Cline et al., 1997). Later, contrast sensitivity testing complemented and extended the assessment of visual function provided by acuity tests. At the cost of more complex and time-consuming procedures, contrast sensitivity measurements yield information about an individual’s ability to see low-contrast targets over an extended range of target size (and orientation). Formally, contrast sensitivity defines the threshold between visible and invisible, which has obvious significance for basic (such as optics, psychological etc.) and clinical vision science (Pelli et al., 2013). A typical contrast sensitivity assessment procedure consists of presenting the observer with a sine-wave grating of a given spatial frequency (i.e. the number of sinusoidal cycles per degree of visual angle). The contrast of the target grating is then varied while the observer’s contrast detection sensitivity (or threshold which is reciprocal of sensitivity) is determined. In general, a contrast sensitivity function (CSF) is defined by the contrast sensitivity as a function of spatial frequency. Luminance contrast is typically defined as the difference between maximum and minimum luminance in a stimulus divided by the sum of the maximum and minimum luminance (called Michelson contrast), and CSFs are typically measured with stimuli that vary sinusoidally across space. Since any signal that varies in space can be described mathematically as the sum of a set of sinusoids that vary in frequency, amplitude and phase (Shatkay, 1995), the human visual system might carry out something akin to a Fourier analysis of the visual scene and represent the visual scene in terms of its spatial frequency components (Teller, 2015). This is one strong reason why researchers generally opt for (sinusoid) grating which is periodic.

The entire literature overview is initially divided into 3 sections based on studies on non-uniformities in luminance only, chromaticity only and in both. Also an additional section is included to discuss previous studies on methodological research.

2.1 NON-UNIFORMITIES IN LUMINANCE

The first psychophysical measurement of the human luminance spatial contrast sensitivity function (CSF) was reported by Schade (1956). Two years later, Schade (1958) was also the first to report psychophysical spatial chromatic CSFs. Van Nes et al. (1967) measured luminance contrast sensitivity as a function of spatial frequency of gratings and mean luminance. They found that the sensitivity is a band pass function which increases with increasing mean luminance and decreases at low and high spatial frequencies. More recently, Kim et al (2013) performed a similar experiment with sinusoidal gratings varied in luminance levels and spatial frequency as well. They found similar results with Van Nes et al. (1967) that the contrast sensitivity increases with luminance; but at some point, the peak sensitivity for a lower luminance (20 cd/m$^2$) is the same as for a higher luminance (150 cd/m$^2$) level for the frequencies between 1 and 3 cpd, shown in Figure 2.1. This demonstrates that the sensitivity saturates at a certain luminance level. An increase of the peak sensitivity with increasing luminance is also reported by Peli et al. (1991) at 1 cpd and Van Nes et al. (1967) at 4 cpd. Van Nes et al. (1967) showed that the sensitivity is independent of the color of the luminance grating and that the frequency at which peak sensitivity occurs depends on the mean luminance. The contrast sensitivity at low frequency might get affected by the
number of visible cycles. Below a critical number, the visibility decreases with decreasing number of cycles. The critical number depends on the mean luminance and ranges between 4 and 8 cycles (Hoekstra et al., 1974).

Apart from periodic luminance patterns, researchers have also investigated the visibility of linear gradients and Gaussian-shaped luminance profiles (McCann et al., 1974; Bijl et al., 1989, 1993; Hamberg, 1993). In all these studies, the luminance profiles were applied on homogenous chromatic stimuli. For a linear gradient, the visibility threshold was found to depend on the relative change in luminance across the stimulus and not on the steepness of the gradient (McCann et al., 1974), which means that the visibility was independent of the viewing distance (because the visual angle of the steepness depends on the viewing distance). For circular symmetric Gaussian luminance profiles, the visibility threshold rapidly decreased with increasing diameter of the profiles, but at some point the thresholds again increased (Bijl et al., 1989). Elliptical Gaussian luminance profiles were found to be more easily visible than circular profiles with the same stimulus area (Bijl et al., 1993; Hamberg, 1993).

![Figure 2.1 A band pass Luminance contrast sensitivity for different spatial frequencies and luminance levels (Kim et al., 2013).](image)

### 2.2 NON-UNIFORMITIES IN CHROMATICITY

Previous research found that the visibility threshold of chromatic contrast in regular chromatic patterns depends on many factors such as the spatial frequency (Mullen, 1985), the direction of the chromaticity transition (Mullen, 1985), the base color (Vogels & Lambooij, 2014), the shape of the waveform (van der Horst, 1969), the luminance of the chromatic pattern (Rovamo et al., 2001), the background luminance (Kim et al., 2013), the velocity of the pattern on the retina (Kelly, 1983) etc. However most of these studies used iso-luminous chromatic gratings, made by superimposing two monochrome gratings (opponent colors: red-green or blue-yellow) whose luminance varied sinusoidally 180° out of phase. But there are less sufficient data on the sensitivity to chromatic contrast for various luminance profiles along with radially symmetric color variations, such as in LED spots.

Mullen (1985) measured the behavior of the chromatic CSF for two color-opponent gratings: red-green and blue-yellow (with uniform background luminance) which were varied by spatial frequencies. She noticed that unlike the band-pass characteristic of the luminance CSF, the sensitivity to chromaticity patterns exhibits a low-pass function, with no low frequencies attenuation even at frequencies below 0.1 cpd. The chromatic sensitivity declines at spatial frequencies above 1 cpd. The visual field size was chosen such that the lowest spatial frequency used could be displayed with at least 4 cycles visible. This was done to eliminate the effect of number of cycles at less than 4 cycles (Howell & Hess, 1978). Eventually, a comparison between chromatic and luminance CSF was presented (shown in Figure 2.2) in which they found that the CSF for a green monochromatic grating (varying in luminance contrast only) is smaller than that of for a red-green chromatic grating at low spatial frequencies below 0.5 cpd and is also smaller than that of for a yellow-blue chromatic grating at spatial frequency below 0.3 cpd.
Van der Horst (1969) measured the contrast thresholds of iso-luminous chromaticity-modulated gratings for various waveforms (sine-, square-, and triangular-wave gratings) and concluded that only the amplitude of the fundamental Fourier component is of significance in the visibility threshold of colored gratings, because both the square wave and triangular wave gratings were perceived same as the pattern of the sine-wave gratings when the spatial frequencies tested were really high i.e. above 6-7 cpd.

Besides, Vogels & Lambooij (2014) also measured visibility thresholds of iso-luminous chromatic grating as a function of six spatial frequencies (0.15, 0.3, 0.5, 1.5, 3 and 5 cpd) for three different base colors (CCT: 2600K, 3800K and 5700K along the black body locus) and four different directions of color change in CIE 1976 u’v’ chromaticity diagram. Figure 2.3a shows the contrast visibility threshold function at only one base color of CCT = 5700K. Thresholds were found significantly smaller for lower CCT (2600K) compared to higher one (5700K) and the shape of contrast threshold function tended to look like a band-pass at lower frequency range, because it slightly decreased from 0.15 cpd to 0.3 cpd and after that it increased with frequency. Also, in line with MacAdam’s findings, an ellipse was fitted through the chromaticity coordinates of the average visibility threshold in each of the four directions. This way of visualizing the data shows that the size and orientation of the ellipse depends on the base color and the spatial frequency of the chromatic pattern. For comparison, the MacAdam ellipse were also plotted along with them (in Figure 2.3b), emphasizing the use of a single threshold based on the MacAdam ellipse is not sufficient to account for the diversity of different spatial frequencies in patterns. The decrease of sensitivity at 0.15 cpd might be explained by not having sufficient number of cycles for low frequencies (Savoy & McCann, 1975).

Recently, Daatselaar & Veelenturf (2015) extended the experiment of Vogels & Lambooij (2014) by taking into account the lower spatial frequencies (0.025 cpd – 0.3 cpd), the number of visible cycles (2-8 cycles) and grating orientations (horizontal and vertical). Interestingly, the contrast threshold function they found was band-pass shaped at lower frequency range (0.025 – 0.15 cpd) and at 2-6 cycles as shown in Figure 2.4. They observed that people are most sensitive when shown with sufficient number of cycles (more than 6 cycles) and concluded that the increase in threshold at lower spatial frequencies is caused by the decrease in number of visible cycles.

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9 Personal communication with M. Lucassen (Philips Lighting Research)
2.3 NON-UNIFORMITIES WHEN BOTH LUMINANCE AND CHROMATICITY ARE VARIED

So far, the research on contrast visibility thresholds are discussed for either isoluminous chromatic stimuli or monochromatic luminance stimuli. However, thresholds for chromaticity differences also depend on the luminance of the chromatic grating. Visibility thresholds decrease with increasing luminance, but it saturates at higher luminance levels (Rovamo et al., 2001). A similar pattern was observed by Kim et al. (2013)’s research with a variation in background luminance level. Contrast sensitivity was measured for chromatic grating stimuli of spatial frequencies ranging from 0.25 to 16 cpd for a wide range of adapting luminance levels (0.02 to 200 cd/m²) under the same viewing conditions. The chromatic thresholds decreased with increasing luminance levels, yet saturated at luminance above 40 cd/m². However, the change in thresholds with decreasing luminance level was found to be more significant compared to that of with spatial frequencies. Interestingly there was little change reported in the shape of the CSF when the luminance level was varied.

Since color vision involves both chromaticity and luminance information, it is always an interesting topic how they interact with each other. To find out if chromaticity and luminance influence each other, DeValois & Switkes (1983) superimposed a yellow-black luminance grating on a red-green chromatic grating and vice versa. This
process is called masking. The stimulus which superimposes another stimulus is called the mask and the superimposed stimulus is called test. Varying the spatial frequencies of both test and mask gratings, they concluded that the luminance grating had little masking or inhibition effect on the detection of the chromatic grating, but the chromatic grating greatly interfered with the detection of the luminance grating presented simultaneously. However, significant masking was seen only when mask and test gratings were identical in spatial frequency. Later, Switkes et al. (1988) varied the masking contrast while keeping the spatial frequency (2 cpd) constant for both mask and test gratings in monocular viewing. They observed that the luminance mask facilitated the detection of the chromatic test grating over a broad range of both subthreshold and suprathreshold contrasts of the luminance mask. A masking effect was found only for high contrast luminance masks. On the other hand, the chromatic grating was found to have masking effect on the detection of luminance test grating for any contrast of the chromatic mask; no facilitation was found at all.

Furthermore, Mullen et al. (2014) also investigated whether contrast detection in color vision can be normalized by luminance contrast, or whether this is a selective process driven only by color or chromatic contrast. They used a method of cross-orientation masking, in which a chromatic grating was superimposed by a 90° out of phase luminance grating (of the same spatial frequency), over a range of spatio-temporal frequencies (0.375-1.5 cpd; 2-8 Hz). They did not find any significant masking effect on the detection of the chromaticity by the luminance mask (under binocular viewing) for higher spatio-temporal frequencies (> 0.75cpd and >2Hz), yet a significant facilitation at low spatio-temporal conditions (<= 0.75cpd and <=2 Hz) was observed.

Whatever we discussed till now applies to either horizontally or vertically aligned sinusoidal gratings. However, for some realistic lighting applications such as LED spot light with color-over-angle effect, both the chromaticity and luminance of the light vary spatially. Figure 2.5 is a perfect example of such a case where the chromaticity content is half a cycle radially symmetric sinusoid and the luminance is Gaussian-shaped. Such a varying luminance profile has peak luminance at the center of the spot and then gradually fades out at its edge. Hence, different positions in the spot differ in both absolute and relative (= absolute luminance at particular position /peak luminance) luminance values.

**Figure 2.5** A simulated LED spot with color-over-angle effect. The spot has a Gaussian shaped luminance on a radially symmetric sinusoid with half a cycle (chromatic content) of base color CCT=6500K.

This kind of stimuli was used by Dross (2013)\textsuperscript{10}, who performed an experiment to measure the acceptability\textsuperscript{11} of color differences in a spot, where a color transition is presented at the center, middle and edge of a simulated LED spot viewed at a distance of 1 m. Since, the spot is radially symmetric, the position of a color transition in the spot can also be expressed in visual angle. The center, middle and edge positions in the spot corresponded to 10°, 20° and 30° visual angle respectively. The color transition were presented with 4 different steepness levels (visual angle of the width of color transition = 1°, 4°, 6° and 9°). In addition, the stimulus was compared to a reference image with a uniform chromaticity and only change in luminance (decreasing in value

\textsuperscript{10} Philips Lighting Research Internal Technical Note

\textsuperscript{11} acceptability thresholds corresponds to the gain at which an average observer will accept the color deviation or transition with a probability of 50%
from center to the edge of the spot gradually). Most recently, Lambooij (2015) extended Dross’s research to find out the visibility thresholds rather than acceptability thresholds. The Gaussian luminance profile used had FWHM (Full Width of Half Maximum) of 16° in visual angle and only one base color CCT=2700K was used. However, previous research (Vogels et al., 2013) shows that the higher the color temperature, the higher both the acceptability and visibility thresholds are. Figure 2.6a shows the stimuli used in the experiment. The 3 different positions in the luminance profile are also represented by 3 different relative luminance values (0.76, 0.34 and 0.09). Figure 2.6b shows the contrast threshold plotted for 4 different steepness and 3 different relative luminance values. The plot clearly shows that the visibility threshold increases with decreasing relative luminance, i.e. the color transition occurs more towards the edge of the spot. Also, more gradual color change demands higher thresholds.

![Figure 2.6a](image1)

**Figure 2.6a** (Above) The participants were shown a stimulus (base color CCT=2700K) with a reference; they had to select which of them had a color transition. (Below) The color transition was made at 3 different positions in the Gaussian luminance profile expressed in visual angle with viewing distance of 1 m; The peak luminance was constant during the experiment (112 cd/m²). 10°, 20° and 30° are the visual angles of the position of the chromaticity profile respectively.

![Figure 2.6b](image2)

**Figure 2.6b** The graph is plotted in logarithmic scale with base 10; 3 relative luminance levels (0.76, 0.34 and 0.09) are shown manually in x-axis and the threshold is expressed as du’v’*1000 in y-axis; thresholds also vary with 4 different visual angles (in degrees) of the steepness of color change (1°, 4°, 6° and 9°).

### 2.4 METHODOLOGICAL RESEARCH

Literature has discussed the effect of different presentation modes of the stimuli on visibility thresholds. For instance, Seuntiens (2002) attempted to find out about the plausible effect of the presentation mode of stimuli on the perception of color gradients in natural images presented in a display. Stimuli were once presented simultaneously as a pair next to each other and once time-sequentially on the same screen position. During the experiment, saturation was changed keeping the hue values of each pixel constant and later, hue was changed keeping the saturation of each pixel constant. Seuntiens did not find any significant difference in the visibility of saturation gradients if the stimuli were presented simultaneously or time-sequentially. But if the hue of the presented color profile was changed, a significant difference between both presentation modes was detected in which presenting stimuli simultaneously caused the thresholds 3-4 times lower than the time-sequential presentation. Later, Hultermans (2003) measured the effect of presentation mode on the visibility of luminance.

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12 Philips Lighting Research Internal Technical Note
13 visibility thresholds focuses on finding out the exact color difference when the stimuli starts not being visible at all which compromises lesser than the method of acceptability on finding the threshold
14 Philips Lighting Research Internal Technical Note
gradients in natural images. He did not find any significant difference between presenting stimuli simultaneously or time-sequentially. Recently, Rosenberger et al. (2012) also studied the effect of presentation mode on the visibility threshold of a color transition in a simulated realistic LED spot. They used two different modes: in the first mode, only one stimulus was shown which is called as ‘no reference’ mode and in the other mode, always two stimuli were presented one after each other. One of them contained a color profile whereas the other did not. This mode is called ‘with reference’. They also tested the effect of the presentation modes for 4 different angles between the horizontal axis of the luminary and the normal vector of the image plane. The visibility thresholds were found almost 2 times lower while the participants saw the test stimulus with a reference image than without a reference (in Figure 2.7).

Figure 2.7 Mean visibility thresholds in terms of 1000 x max (∆u'v') for different presentation modes as function of angles (angle between the horizontal axis of the luminary and the normal vector of the image plane) for a viewing distance of 2 m and 5 m. The error bars correspond to the 95% confidence interval (Rosenberger et al., 2012). Without reference causes almost twice thresholds than with reference at both viewing distances.
3 MOTIVATION FOR CURRENT RESEARCH

3.1 UNEXPLORED TOPICS IN PREVIOUS RESEARCH

We have discussed the visibility thresholds study by Lambooij (2015) based on Dross (2013)’s experimental setup. However, there are still some areas unexplored in that research which can further be analyzed. Color transition occurred at different positions in the spot. Yet, the peak luminance (112 cd/m²) was constant for all the variations. Lambooij (2015) showed that the visibility threshold of a CoA effect depends on the position, or relative luminance, or absolute luminance values in the spot. This still does not explain everything, since the absolute and relative luminance at any position are inter-correlated to each other: changing position would change both absolute and relative luminance values in the same luminance profile with a fixed peak luminance. Hence, the impact of relative and absolute luminance on the visibility of CoA transitions should be independently determined. Four different combinations between absolute and relative luminance at any position could be possible in a spot if any of the lighting parameters such as peak luminance, position etc. changes. They are explained with specific conditions:

1) Both absolute and relative luminance vary: The position of the color transition in the luminance profile is varied while the peak luminance is kept constant. The width (FWHM) of luminance profile is constant also. Figure 3.1 explains it schematically.

![Figure 3.1](image1.png)

**Figure 3.1** Schematic diagram of a Gaussian shaped luminance profile. If the peak luminance is kept constant, each and every position in the luminance profile will have different both absolute and relative luminance values.

2) Constant relative luminance and varying absolute luminance: The position of the color transition in the luminance profile is kept constant while the peak luminance is varied. The width (FWHM) of luminance profile is not changed. Figure 3.2 explains it schematically.

![Figure 3.2](image2.png)

**Figure 3.2** Schematic diagram of a Gaussian shaped luminance profile. If the peak luminance is halved, each and every position in the luminance profile of the right figure will contain absolute luminance values exactly half as that of the left one. But relative luminance is same for both of them as the position is kept constant (Position₁ for both).
3) **Varying relative luminance and constant absolute luminance:** The position of the color transition in the luminance profile should be changed if the peak luminance is varied. The width (FWHM) of luminance profile is not changed. Figure 3.3 explains it schematically.

**Figure 3.3** Schematic diagram of a Gaussian shaped luminance profile. If the peak luminance is halved, to keep absolute luminance at any position constant between both the luminance profiles, the position should be changed (from Position$_1$ to Position$_2$) in new luminance profile.

4) **Both absolute and relative luminance constant:** The position of the color transition in the luminance profile should be changed if the peak luminance is kept constant, but the width (FWHM) of luminance profile is varied. However, the color transition should occur relatively at the same position (where relative luminance is exactly same) between those profiles. Figure 3.4 explains it schematically as well.

**Figure 3.4** Schematic diagram of a Gaussian shaped luminance profile. If the peak luminance is kept constant, but the width of luminance profile is increased, to keep both absolute and relative luminance constant, the position should be changed (from Position$_1$ to Position$_3$) in new luminance profile such that relatively Position$_1$ in left profile = Position$_3$ in right profile.

Also, the relative luminance values were all high (>0.87) in Lamboolj (2015)’s study, meaning that the color transitions occurred relatively close to the center of the spot. To cover a range of relative luminance values at which CoA occurs, some lower relative luminance values should also be tested such that the relative luminance < 0.01.
3.2 CURRENT STUDY

We have discussed about color-over-angle (CoA) effects (section 1.2.2) that persists in LED spot applications. For a standard Gaussian function as realistic luminance profile of an LED spot, the visibility threshold of CoA effect could be a function of several lighting parameters, such as the peak luminance, the size and shape of the luminance profile, the steepness (=1/width of the color transition) of the chromaticity profile, and the position of the chromaticity profile in the spot. For instance, we have discussed Kim et al. (2013)’s study where chromatic contrast threshold decreases if the absolute luminance level is increased for an iso-luminous chromatic grating until a certain value where the effect saturates. Furthermore, literature has shown that under some conditions the detection of a chromatic grating is influenced by the spatial frequency of the luminance profile of the grating (Mullen et al, 2014). In addition, Vogels & Lambooij (2014) found evidence that chromatic contrast threshold (or sensitivity) of iso-luminous grating depends on spatial frequency of the chromatic change which is analogous to the slope or steepness of the chromatic variation in the spot. In addition, it is also known that experimental methodology could have an effect on chromatic contrast sensitivity (Rosenberger et al., 2012) which reveals that the sensitivity to chromatic differences in a spot increases when the spot can be compared to a spot without color change.

3.2.1 RESEARCH QUESTIONS & HYPOTHESIS

This leads to the following research questions: “how is the visibility threshold of a gradual change in the chromaticity of a spot light affected by: (1) the position of the chromaticity profile, (2) the peak luminance of the Gaussian luminance profile, (3) the width of the Gaussian luminance profile, (4) the steepness of the chromaticity profile, and (5) the presentation mode (with/without reference)”?

For some research questions, we can formulate a hypothesis. For research question 2, two sub-questions can further be defined as discussed in section 3.1:

“how is the visibility threshold of a gradual change in the chromaticity of a spot light affected by the peak luminance: (2a) while keeping the relative luminance at the position of the chromaticity profile constant and (2b) while keeping the absolute luminance at the position of the chromaticity profile constant.

In the following section, the research questions are discussed along with a hypothesis whenever possible to form, otherwise as an explorative question.

**Question 1:** Changing the position in a spot with a Gaussian luminance profile changes both relative and absolute luminance at the position of the chromaticity profile if the peak luminance of the luminance profile is constant (Figure 3.1). Lambooij (2015) tested the effect of positions on visibility thresholds, and observed that the visibility thresholds increased if the CoA shifts more towards the edge of the spot which leads us to the following hypothesis:

_Hypothesis: The visibility threshold of a gradual CoA in a spot with a Gaussian luminance profile is increased if the position of the chromaticity profile is more towards the edge of the spot._

However, Lambooij (2015) tested only for a base color of CCT = 2700 and the lowest relative luminance tested (>0.01) was also not that low.

**Question 2a and 2b:** The individual impact of either relative luminance or absolute luminance cannot be inferred from the hypothesis of Question 1. They should be independently determined by keeping the other constant at a time. Kim et al. (2013) studied the effect of luminance level on the contrast sensitivity or the reciprocal of the visibility threshold at constant relative luminance, and found that the visibility thresholds increased with
decreasing luminance level until a certain point where it saturated. This leads us to formulate the below hypothesis:

**Hypothesis:** The visibility threshold of a gradual CoA in a spot with a Gaussian luminance profile is increased if the peak luminance is decreased while keeping the relative luminance at the position of the chromaticity profile and the position itself constant, but the absolute luminance changes (Figure 3.2).

As the effect of the peak luminance on the visibility thresholds at constant absolute luminance while the relative luminance changes (Figure 3.3), is still unexplored for any prediction to make, we will explore Question 2b instead of formulating a hypothesis.

**Question 3:** Figure 3.4 shows a scenario of having constant absolute and relative luminance at a position while the width of the luminance profile is changed. Mullen et al. (2014) investigated that under some conditions the detection of a chromatic grating is influenced by the spatial frequency of the luminance profile of the grating. However, they used a completely different experimental setup than what we use in the current study and also involved temporal frequencies in the experiment. So, the effect of width of the Gaussian luminance profile on the visibility thresholds is also unexplored yet, which leads us to test the following question in explorative fashion:

“how is the visibility threshold of a gradual CoA in a spot with a Gaussian luminance profile affected by the width of the luminance profile, while both relative and absolute luminances are constant but the position is changed”?

**Question 4:** Furthermore, Vogels & Lambooij (2014) observed that for an iso-luminous chromatic grating, lower spatial frequencies (in which steepness of chromatic change is more gradual) of the grating result in higher visibility thresholds considering the grating area is fixed and the number of visible cycles is also less. This leads us to the next hypothesis:

**Hypothesis:** The visibility threshold of a gradual CoA in a spot with a Gaussian luminance profile is increased if the chromaticity transition is more gradual.

**Question 5:** Rosenberger et al. (2012) found that the visibility thresholds were almost 2 times lower if the participants had the possibility to see the test stimulus is accompanied by a reference stimuli (without a color transition) in a time sequential manner than seeing without any reference. This leads us to the below hypothesis:

**Hypothesis:** The visibility threshold of a gradual CoA in a spot with a Gaussian luminance profile is increased if the color profile is presented without a reference stimulus compared to with a reference stimulus.
This section describes the experiment to test the effects of the lighting parameters on the visibility thresholds of CoA. The approach was to simulate spots with CoA on a display and performing a perceptual experiment to determine the visibility thresholds.

4.1 METHOD

4.1.1 EXPERIMENTAL DESIGN

Since, the visibility threshold of a CoA can be influenced by several factors, including all of the factors that affect visibility threshold would increase the number of conditions as well as the overall complexity of the experimental design. Also some of the parameters such as steepness and presentation mode, are not tested for all conditions. The smoothness of some transition of the chromaticity profile at the edge of a spot (having very low relative luminance) could not be accommodated within the limits of the image size. To simplify the data analysis and test all the stated hypothesis and explorative questions, we decided to have a dedicated design for each of them. These are discussed separately below. Along with that, one pilot was also performed to test the effect of different types of the luminance profile, such as Gaussian and uniform, whose design is also discussed here.

Note that the relative luminance is used in the design whenever we wanted to test the effect of position in the spot. This is because the relative luminance defines the positions correctly even if the width of the luminance profile changes in a spot (Table 4.1). For different widths of the luminance profile, the positions were chosen such that they result in similar relative luminance values between the two profiles.

Table 4.1 Abbreviations and values of several relevant parameters to luminance profiles for the position of the chromaticity transition. SW and LW stand for small/large width of luminance profile; HPL and LPL stand for high/low peak luminance; P stands for position in the spot measured in visual size (visual angle); RL and AL stand for relative luminance and absolute luminance at corresponding positions respectively; S, M and G represent steepest, medium steep and gradual chromatic changes respectively. In each width of the luminance profiles, the higher the suffix of the position, the nearer the chromaticity transition towards the center of the spot is. For both relative and absolute luminance values, it holds that a higher suffix indicates higher luminance values.

<table>
<thead>
<tr>
<th>Visibility thresholds</th>
<th>SW (visual angle of FWHM: 5.6°)</th>
<th>LW (visual angle of FWHM: 11.2°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width of luminance profile in visual size</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak luminance</td>
<td>HPL (154 cd/m²)</td>
<td>LPL (77 cd/m²)</td>
</tr>
<tr>
<td>Position (spatial)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P₁</td>
<td>P₃</td>
<td>P₂</td>
</tr>
<tr>
<td>Relative luminance</td>
<td>RL₁ (0.009)</td>
<td>RL₂ (0.009)</td>
</tr>
<tr>
<td>Absolute luminance (cd/m²)</td>
<td>AL₂ (1.4)</td>
<td>AL₄ (10)</td>
</tr>
<tr>
<td>Steepness (visual angle of the width of chromaticity change)</td>
<td>S (0.5°), M (2.8°) and G (9°)</td>
<td>S (0.5°), M (2.8°) and G (9°)</td>
</tr>
</tbody>
</table>
Design 1: The effect of position of the chromaticity transition in the spot: The design is a full factorial (4x2x2) between-subjects design which consists of 4 different positions with 4 different relative luminance values (RL1, RL2, RL3 and RL4), 2 widths of the luminance profile (SW and LW) and 2 steepness levels (S and M). All 4 positions are tested only for peak luminance of LPL. The data recorded with the presence of reference stimulus are only considered.

Design 2: The effect of peak luminance: This is tested for two different cases such that when the relative luminance at positions are constant between two spots with varying peak luminances and when the absolute luminance at positions are constant between two spots with varying peak luminances.

   a) when the relative luminance at positions is fixed: The design is a full factorial (2x2x3x2) between-subjects design which consists of 2 peak luminance levels (LPL and HPL), 2 widths of the luminance profile (SW and LW), 3 steepness levels (S, M and G) and 2 positions with relative luminance of RL1 and RL3. The data recorded with the presence of reference stimulus are only considered.

   b) when the absolute luminance at positions is fixed: The design is a full factorial (2x2x3x2) between-subjects design which consists of 2 peak luminance levels (LPL and HPL), 2 widths of the luminance profile (SW and LW), 3 steepness levels (S, M and G) and 2 positions with absolute luminance of AL2 and AL4. The data recorded with the presence of reference stimulus are only considered.

Design 3: The effect of width of the luminance profile: It is a full factorial (2x2x3x4) between-subjects design which consists of 2 widths of the luminance profile (SW and LW), 2 peak luminance levels (LPL and HPL), 3 steepness levels (S, M and G) and all 4 positions with 4 different relative luminance values (RL1, RL2, RL3 and RL4). The data recorded with the presence of reference stimulus are only considered.

Design 4: The effect of steepness of the chromaticity transition: It is a full factorial (3x2x3) between-subjects design which consists of 3 steepness levels (S, M and G), 2 widths of the luminance profile (SW and LW), and 3 different combinations of peak luminance and positions (expressed in relative luminance) such as [HPL & RL3], [LPL & RL3], and [LPL & RL4]. The data recorded with the presence of reference stimulus are only considered.

Design 5: The effect of presentation mode (with/without reference): It is a full factorial (2x3x2) between-subjects design which consists of 2 presentation modes (reference present? - yes or no), 3 steepness levels (S, M and G), and 2 widths of the luminance profile (SW and LW). The conditions are only tested for the peak luminance of LPL and one position with relative luminance of RL3.

Design 6 (pilot experiment): The effect of the type of the luminance profile: The design is a full factorial (2x3) between-subjects design which consists of 2 types of the luminance profile (Gaussian and uniform) and 3 steepness levels (S, M and G). The position of the chromaticity change was kept constant such that the visual angle of the midpoint of that change was 22°. No reference was shown along with the test stimulus. The width of the Gaussian luminance profile was selected as LW.

In total, 36 conditions are tested in the main experiment, an overview of which is presented in Appendix 8.2. Given the large number of conditions to be tested, the entire experiment was divided into 3 different sessions, each of half an hour in average. Each of the sessions were planned with a peak luminance fixed during the entire session. Each session contained 2 or 3 series of images appearing one after the other. For each series, the width of the luminance profile, the peak luminance and the presentation mode were kept fixed, the stimulus only varied by the steepness of the chromaticity transition and its position in the spot (see Table 4.2). The order of both the sessions and the series of images were randomized between participants to prevent any kind of order bias. In session 2 and 3, participants were shown images with both ‘with reference’ and ‘without reference’ conditions in separate series. But in the session 1, only ‘with reference’ spots were shown. Hence, the average
luminance for each and every series in each session differed based on the presence of reference image, the width of luminance profile and the peak luminance tested for that series of images.

Table 4.2 All series for each session tested; the order of the series was actually randomized during experiment; steepness G is not tested when relative luminance is either RL1 or RL2.

<table>
<thead>
<tr>
<th>Sessions</th>
<th>Peak luminance</th>
<th>Series 1</th>
<th>Series 2</th>
<th>Series 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Rel. lum.: RL1, RL3 Reference present</td>
<td>Rel. lum.: RL1, RL3 Reference present</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rel. lum.: RL1, RL3 Reference present</td>
<td>Rel. lum.: RL1, RL3 Reference present</td>
<td>Rel. lum.: RL3 No reference</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rel. lum.: RL2, RL4 Reference present</td>
<td>Rel. lum.: RL2, RL4 Reference present</td>
<td>Rel. lum.: RL3 No reference</td>
</tr>
</tbody>
</table>

4.1.2 PARTICIPANTS

For the pilot experiment, only three participants (3 male; mean age = 33 years, standard deviation = 13 years) volunteered who are either student or working professional in Philips Lighting research. All of them had prior knowledge on visual perception and lighting experiments.

For the main experiment, twenty-one participants (13 male and 8 female; mean age = 27 year, standard deviation = 6.5 years, range = 22 to 52 years) volunteered. All participants are either students or employees working at Philips Research, Eindhoven. Among them, three persons had expert knowledge on visual perception and psychophysical experiments; two had decent knowledge and previous experience with staircase method and others had very limited/no experiences with lighting experiments. All participants successfully passed the Ishihara Color Vision test, so they had no color vision deficiencies.

4.1.3 STIMULI

Several pilots were performed to decide on the range of steepness levels of the chromaticity profile, widths of the luminance profile, the peak luminance and the expected range of color differences to be tested. The simulation of LED spots is done in MATLAB 2015b software. The stimuli used in this experiment are characterized by a luminance profile and a chromaticity profile (Figure 4.1) which are discussed in the following sections.

4.1.3.1 LUMINANCE PROFILE

Among many non-linear symmetrical waveforms, a standard Gaussian distribution function is considered as luminance profile because it resembles a realistic spot lighting application. Equation 4.1 represents the formula of a 2-dimensional (x,y) Gaussian function G centered around (x₀,y₀), σ is the standard deviation of the function assuming σₓ = σᵧ, being equal.

\[ G(x, y) = e^{\left(-\frac{(x-x₀)^2+(y-y₀)^2)}{2\sigma^2}\right)} \]  (4.1)
During the experiment, the luminance profile is varied by its width or technically, by its FWHM (full width at half maximum) and its maximum level. FWHM is expressed as the visual angle measured from 50 cm of the screen (our standard viewing distance). We selected two FWHM, one being twice as large as the other (11.2° and 5.6°). These values are based on the largest spot that the display is able to show, which is limited in the use of a reference spot side by side.

4.1.3.2 CHROMATICITY PROFILE
The chromaticity profile is basically a sinusoid look alike waveform of half a cycle with flattened maximum absolute value. The upper and lower values of that waveform represent two different color points. Figure 4.1 presents a schematic diagram of a CoA stimulus separated into chromaticity and luminance profiles accordingly. The slope of the transition from upper to lower values is represented as degree of steepness. Three different steepness values are used which are expressed as the visual angle of the transition from one color to another: 0.5°, 2.8° and 9°. Table 4.3 provides the position of the midpoint of the chromaticity transition which is varied by both the widths of the luminance profile and its positions in the spot.

Table 4.3 Visual angles of the midpoint of the chromaticity change for different widths of luminance profile and its position in the spot. Note that both the luminance profile and the chromaticity profile are radially symmetric.

<table>
<thead>
<tr>
<th>Width of luminance profile</th>
<th>Relative luminance at different positions</th>
<th>visual angle of the position of the midpoint of the chromaticity transition</th>
</tr>
</thead>
<tbody>
<tr>
<td>SW</td>
<td>RL1</td>
<td>14.3°</td>
</tr>
<tr>
<td>SW</td>
<td>RL2</td>
<td>13.4°</td>
</tr>
<tr>
<td>SW</td>
<td>RL3</td>
<td>11°</td>
</tr>
<tr>
<td>SW</td>
<td>RL4</td>
<td>9.6°</td>
</tr>
<tr>
<td>LW</td>
<td>RL1</td>
<td>28.6°</td>
</tr>
<tr>
<td>LW</td>
<td>RL2</td>
<td>26.4°</td>
</tr>
<tr>
<td>LW</td>
<td>RL3</td>
<td>22°</td>
</tr>
<tr>
<td>LW</td>
<td>RL4</td>
<td>19°</td>
</tr>
</tbody>
</table>

In CIE 1976 u’v’ color space, D65 on the Planckian locus is determined. The color transition is along the tangent of the Planckian locus with the D65 point being the center. The larger the color difference, the further away from the D65 the color points are. For example, Figure 4.1 (left) shows a simulated LED spot with base color CCT = 6500K where the bluish white center disk transits to a yellow ring surrounding it, imitating a color-over-angle effect. Figure 4.1 (right) shows the direction of chromaticity transition at D65 white reference point on the Planckian locus.

4.1.4 EXPERIMENTAL SETUP
Figure 4.2 shows a schematic diagram of the entire experimental setup. The inter-distance between test and reference stimulus was kept constant (visual angle = 1.5°) to prevent the effect of separation on the visibility thresholds. Research (Vogels et al., 2013) has shown that the further apart the test and reference stimuli are in an image, the higher the visibility threshold is. The test and reference stimuli are placed randomly in right and left side of the image to prevent any location bias by participants. The entire experiment is done in Philips Lighting Research lab, Eindhoven.

15 Philips Lighting Research Internal Technical Note
**Figure 4.1** (left) Schematic way of deriving a CoA stimulus into two different components: chromaticity and luminance profile, (right) Red line shows the direction of chromaticity transition; higher color differences shift the chromaticity of the color points (equally distant from D65 point) towards (blue, yellow) region; two color points are drawn for clear understanding in both left and right figures.

**Figure 4.2** Schematic view of the experimental setup. Different sizes of stimuli are used in the experiment. The circles shown are stimuli in the screen. The dotted lines are used to display the visual angle of the inter-distance between two stimuli.
4.1.5 APPARATUS

To display the stimuli, a NEC Spectraview 272, i.e. a LED backlit LCD display monitor of display area 61 cm (width) x 33.3 cm (height), is used with a color depth of 10bit per primary and a 0.233 mm pixel pitch, and a resolution of 2560x1440. Windows 7 is used as operating system.

The brightness is set at 220 cd/m$^2$, which is the upper limit for that screen to produce a spatially uniform brightness. To verify the homogeneity level of luminance as well as chromaticity over the whole screen, a SpectraDuo Spectroradiometer PR-680 is used to measure color points at several screen positions by putting up iso-luminous monochrome red, blue, green, white and black images one after the other. The analysis of the measurement data shows that the display offers a high level of homogeneity in color (chromaticity & luminance) over the entire screen.

The display is set to native color gamut with white point of D65 (around 6500K), gamma of 2.2. Native means that a default value for the color temperature of LCD panel is same as the color temperature of the backlight.

The monitor is calibrated with a Jeti Specbos 1211 that measures X, Y and Z values related to the iso-luminous monochrome red, blue, green, white and black images put up on the display. Based on this information, the XYZ to RGB transformation matrix$^{16}$ is determined specific for this display. Since in native mode, the impact of the black level is however compensated by the NEC display itself automatically while displaying images, the black level is not incorporated in the calculation of the transformation matrix.

During the experiment, ambient lighting is used. Previous experiments have shown ambient light did not have a significant effect on the visibility thresholds in sinusoidal color gratings, and greatly improves the visual comfort during the experiment$^{17}$. However, ambient light can change our state of adaptation and pupil size, leading to a change in retinal illumination (Watson & Yellot, 2012).

We used the same ambient lighting setting as mentioned above. Figure 4.3 shows the experimental setup with ambient lighting (luminance is color coded). Fluorescent tubes are used to provide background lights on the wall behind the monitor. The CCT of those tubes is 2800K and the average luminance level of the monitor surround is around 100 cd/m$^2$. The tubes produce a vertical luminance gradient, but no direct light on the monitor.

4.1.6 PROCEDURE

Upon entering the experiment room, the participant was asked to have a seat and was given a moment to read and sign the informed consent (Appendix 8.5). They went through the Ishihara test. An oral introduction was given about the scope of the project (see Appendix 8.4 for the full text). Any questions raised by the participants were answered carefully. Participants performed the entire experiment using a chinrest at 50 cm viewing distance from the screen (Figure 4.4).

To make the task of the experiment clear to participants, they were trained with a few demo images with different color differences ($\Delta u'v'$) and were asked exactly the same experimental questions: 1) where do you see a color transition – left or right, when reference is present, 2) do you see a color transition – yes or no, when there is no reference. If the reference is present, participants responded by left/right keystroke in the keyboard to indicate the test stimuli to be present left or right respectively. Otherwise, yes/no was indicated by right/left keystroke. They were advised to look at the entire image, and not just to look at some certain areas in order to make a decision.

$^{16}$ http://www.brucelindbloom.com/
$^{17}$ Philips Lighting Research Internal Technical Note
Figure 4.3 Experimental setup with ambient light at the back wall (Philips Lighting Research, Eindhoven). Luminance level is color coded.

Figure 4.4 a) Position of the chin rest in front of the stimulus display; b) & c) A participant is performing the experiment. Note that the ambient light is present.
To avoid large differences in the level of chromatic adaptation, participants were also advised not to spend too much time (approx. 5 secs each image) on one image. However, with a reference, the test and reference stimuli are scanned successively which signifies that the chance of chromatic adaptation is lesser. Without a reference, the chance seems bigger as they spend more time on a single spot to make decision.

After the training, the actual experiment started. For each session, participants followed the below steps:

1) They viewed a uniform adaptation image of base color CCT = 6500K with a luminance corresponding to the average luminance of the images to be shown in that series of the sessions, for 10 secs.
2) They were shown an image consisting of two simulated LED spots on the screen. Both spots had the same luminance profile. One of the spots had color variation (a yellowish or brownish colored ring surrounding a blueish white color filled circle) and the other spot had a uniform color but varied with luminance intensity. They had to indicate which of them had color variation by pressing left/right keystroke based on its location on the screen. In some conditions, only one spot was visible in which the same color variation happened. They had to respond if they could see the color variation by pressing left/right keystroke indicating no/yes. After the decision was made and responded by participants, the same adaptation image was shown for 1.5 secs before showing the next target image.
3) They started with a large color difference ($\Delta u'v'$) so that they could easily detect the color variation and also learn about what to look for. The successive images were shown using staircase method.
4) The participants were asked to make a guess whenever they were not able to find any color difference in the stimulus, most likely when they were close to the visibility thresholds.

Two different staircase procedures were used based on the presence or absence of a reference stimulus. When the reference was present: the visibility thresholds were determined using the one-down/three-up\(^{18}\) weighted staircase method that converges to 75\% correct responses (discrimination thresholds). When the reference was absent: the visibility thresholds were determined using the one-down/one-up weighted staircase method that converges to 50\% correct responses (detection thresholds). The current stimulus that appeared was dependent on the response of the preceding stimulus with the same steepness or relative luminance. After each wrong answer the staircase reversed back a number of steps. In order to accelerate the converging process, the step size was changed after each two reversal points with 10, 5, 2 and 1. In total, eight reversal points were measured and the last four reversal points were averaged to determine the visibility thresholds.

The color difference ranges provided to the Staircase method were not constant for all 36 conditions. For example, for a stimulus with the steepness of $S$, peak luminance of HPL and relative luminance of RL4, the maximum color difference of the chromaticity profile ranged from 0 to 0.01 $\Delta u'v'$, with step size of 0.0001 $\Delta u'v'$, and from 0.011 to 0.06 $\Delta u'v'$, with step size of 0.00245 $\Delta u'v'$ (total of 122 steps). But for a stimulus with steepness of $M$, peak luminance of LPL and relative luminance of RL1, the maximum color difference ranged from 0.008 to 0.03 $\Delta u'v'$, with steps of 0.00022 $\Delta u'v'$, and from 0.031 to 0.06 $\Delta u'v'$, with steps of 0.00145 $\Delta u'v'$ (total of 122 steps). The importance of the upper range of maximum color difference is to provide the participants with a clear notion of the CoA effect whereas the thresholds lied in the lower range. That is why the steps were made much smaller in the lower range. The entire range of the maximum color differences along with the step size used in staircase per condition is presented in Appendix 8.3.

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\(^{18}\) In a 1-down/3-up staircase method, the stimulus level (e.g. color difference in our design) is changed upward after an incorrect response and downward after a correct response, and the size of the upward step is three times that the size of the downward step.
The data was analyzed with a statistical software Stata 13.0. We performed several repeated-measures Analysis of Variance (ANOVA). First, the assumption of normality, implying that the sampled distribution of variables should be normal when included in significance tests, is evaluated before doing the ANOVA. However, the assumption doesn’t mean that the overall distribution of the dependent variable should be normal, but it means that it should be normally distributed at each unique level of the predictor variables (Field, 2013). For each of the designs that are going to be analyzed with full factorial and one-way ANOVA, data are checked for required assumptions (normality, homoscedasticity and independence) before doing ANOVA.

Some outliers were found in the data for different designs using standardized value which are discussed per design in section 4.2.2. The most deviated and influential ones are not included in the respective design.

In all designs, a logarithmic transformation of data is used to make the data normal whenever the normality assumption failed. But only for design 5, i.e. the effect of presentation mode, no transformation did actually help to make the data normally distributed. And this restricts us to do an ANOVA because of the failure of normality assumption. However, an ANOVA is not very sensitive to moderate deviations from normality. Simulation studies, using a variety of non-normal distributions, have shown that the false positive rate is not affected very much by this violation of the assumption (Glass et al., 1972; Harwell et al., 1992; Lix et al., 1996). Hence, performing an ANOVA is not rejected eventually. Besides, we performed a Kruskal-Wallis test after ANOVA to cross validate the results as we doubt on ANOVA’s normality assumption (Hamilton, 2009) for that particular design.

Only for design 4, i.e. the design related to the effect of steepness, the test for homoscedasticity failed. However, we have groups of equal sample size and ANOVA is relatively robust to the violations of homogeneity, it would not be fatal to our analysis even if the variance between groups are not equal (Garson, 2012).

Finally, as the data in our experiment are collected from different participants in different sessions to perform between-subject repeated measures, the data can be assumed recorded as independent to each other. However, the designs to be tested have overlapped data sets among each other. So, performing ANOVA on them one after other signifies that the type 1 error is likely to propagate through all and correction in the significance level is required before going with the next design. However, we decided to ignore that problem for the simplicity of the entire experiment and consider the significance level ($\alpha$) of 0.05 for the test of each design.

After checking the assumptions, we performed several repeated-measures ANOVA that included the independent variables such as peak luminance, width of the luminance profile, steepness and position of the chromaticity transition in the spot and also presentation mode (reference present/absent) based on the designs discussed above and visibility thresholds as dependent variables. The research questions are answered by the main effects of the independent variables and later hypothesis are also discussed using pairwise comparisons. The pairwise comparisons are discussed with Tukey’s HSD post hoc tests along with Bonferroni correction on significance level whenever necessary.

For a complete exploration of the effect of $n$ independent variables on one dependent variable, an ANOVA includes all combinations between those independent variables such as their main effects, and all possible interactions between them, which results in a total of $2^{n-1}$ tests performed. Standard Bonferroni correction was used to adjust the significance level ($\alpha_{adj}=\alpha/N$, where $N$ is the number of tests).

Last, but not the least, partial eta squared ($\eta^2_{\text{partial}}$) values were used as the effect size of the various independent variables on depend variables, such that $\eta^2_{\text{partial}} \leq 0.01$ refers to small effect; $\eta^2_{\text{partial}}$ around 0.06 refers to medium effect, and $\eta^2_{\text{partial}} > 0.14$ refers to large effect.
4.2 RESULTS

4.2.1 RESULTS FROM PILOT EXPERIMENT

To test the effect of different types of the luminance profile on the visibility thresholds, the data were selected from Design 6. Figure 4.5 shows the plot of the visibility thresholds for two different types of luminance profile: Gaussian and iso-luminant/uniform at three different steepness levels (0.5°, 2.8° and 9°). Since only three participants were involved, we did not perform a statistical test. Overall, the Gaussian luminance profile always leads to higher visibility thresholds than the uniform profile. Large difference in visibility thresholds between them (more than a factor of 2) could be found especially for smoother steepness levels.

Figure 4.5 Pilot experiment: visibility thresholds and their 95% CI as function of two different types of the luminance profile (x-axis) for three different steepness levels of chromaticity transition (different bar graph); visibility thresholds are expressed as Δu’v’.

4.2.2 RESULTS FROM THE MAIN EXPERIMENT

The experiment yielded visibility thresholds for each of the 36 conditions, of which 30 are tested with a simultaneously presented reference stimulus whereas the other 6 are tested without any reference.

Since, we aimed to test the formed hypotheses or few sub-questions of the research questions (section 3.2.1), we did not perform a full ANOVA with all independent variables included. Instead, we tested few repeated measures ANOVA on the independent variables that were required to test the corresponding research questions only.

Figure 4.6 (left and right) plots the visibility thresholds and their 95% confident intervals for two widths as function of four different relative luminance values for three different chromaticity steepness levels and two different peak luminance levels. These data are only when a reference stimulus is shown along with the target stimulus. We used the abbreviations of different parameters stated in Table 4.1 for easy reading.

Figure 4.6 clearly shows the impact of position in the spot (which is proportional to the relative luminance). The visibility thresholds increases as the chromaticity transition occurs further towards the edge of the spot, possibly in a nonlinear fashion. Unlike at either RL1 or RL2, we do not see any large difference in the visibility thresholds between RL3 and RL4 unless the chromaticity transition is smooth (e.g. for G).

The visibility thresholds seem to depend on the peak luminance (HPL & LPL), the relative luminance (RL1, RL2, RL3 & RL4) and steepness (S, M & G) of chromaticity transition in the spot. The width of the luminance profile also impacts the visibility thresholds, especially when the relative luminance values are low. Comparing relative luminance levels between peak luminance levels LPL and HPL, the visibility thresholds are always higher for the LPL. Visibility thresholds is also changed by different steepness values of chromaticity transition such that only M and G are affected by the peak luminance whereas S is not.
Figure 4.6 Visibility thresholds (with 95% confidence interval) for different widths of luminance profile (two plots side by side) and three steepness levels (different line type) as function of relative luminance (RL in x-axis) under two different peak luminances (different filling type of markers). Data points tested only at one relative luminance are shown without lines. Data are labeled such that: the first letter of the labels tells either steepest (S), medium steep (M) or gradual (G); the second and third letters represent either high peak luminance (HPL) or low peak luminance (LPL) and the last number represents the number in relative luminance (such as ‘1’ if visibility thresholds is measured at RL1) (see Table 4.1); visibility thresholds are expressed as $\Delta u'v'$. This image is also present in Appendix 8.6 with a high resolution.

The visibility thresholds measured at same absolute luminance values (SHPL1&SLPL2, SHPL3&SLPL4; MHPL1&MLPL2, MHPL3&MLPL4) are also compared between LPL and HPL; yet varying peak luminance levels does not seem to affect the visibility thresholds. There seems to be an exception when the steepness is very smooth such that the visibility thresholds between GHPL3 and GLPL4 look slightly different even though they have same absolute luminance, but this might not be significant.

Besides, a larger width (LW) of the luminance profile seems to result in a higher visibility thresholds, especially at RL1 and RL2. However, for the steepest chromaticity transition, the visibility threshold seems not affected by the width. Although the visibility thresholds for relatively smoother changes (e.g. M and G) do not look different between SW and LW, there is a big change noticed at RL1, especially at LPL.

Participants are also found to detect the CoA variations quite differently at very smooth chromaticity transition, causing a higher 95% confidence interval. Noteworthy is that the visibility thresholds for the steepest chromaticity transition is not affected either by the peak luminance or by the relative/absolute luminance. The smoothest chromaticity transition results in the highest thresholds.

In the following sections, the effects of different factors or independent variables on the visibility thresholds of a CoA variation in a spot are statistically analyzed and discussed separately.

4.2.2.1 EFFECT OF POSITION (RELATIVE LUMINANCE) OF CHROMATICITY TRANSITION IN THE SPOT

To test the effect of position or the relative luminance on the visibility thresholds, the data were selected from Design 1. This test aimed to validate the hypothesis of Question 1. At first, the data of Design 1 was standardized and four outliers were found. Excluding them from the data set, a log transformation was performed on the remaining data which confirmed its normal distribution using both Skewness/kurtosis ($s=0.7454$, $k=0.3601$, $p=0.6223$) and Shapiro-Wilk ($W=0.9961$, $V=1.133$, $p=0.3829$) tests. Cook-Weisberg test revealed that the data sets were having constant variance ($p=0.1789$).
A repeated measures ANOVA was performed with relative luminance as independent variable and visibility thresholds as dependent variable on the transformed data of Design 1. It shows that the main effect of the relative luminance \( F(3,328) = 136.64, p < 0.001, \eta^2_{\text{partial}} = 0.5556 \) is significant on the visibility thresholds and it has a very large effect size.

Post hoc analyses (between six relative luminance pairs) were performed which revealed that the visibility thresholds at those relative luminances are significantly different from each other \( (p<0.005) \). The visibility threshold at RL1 is the highest \( (M=0.0133, SD=0.0069) \) whereas at RL4 it is lowest \( (M=0.0035, SD=0.0015) \). Hence, \( \text{threshold}_{RL1} > \text{threshold}_{RL2} > \text{threshold}_{RL3} > \text{threshold}_{RL4} \). The adjusted significance level was 0.05/6 = 0.0083.

### 4.2.2.2 EFFECT OF PEAK LUMINANCE OF THE LUMINANCE PROFILE

To test the effect of peak luminance on the visibility thresholds, the data were selected from Design 2a and 2b respectively. Two repeated-measures ANOVAs were performed to find out the effect of peak luminance on the visibility thresholds while keeping either the relative or the absolute luminance of the chromaticity profile constant. Figure 4.7 shows the visibility thresholds for these two cases.

**Case 1: At constant relative luminance**

This aimed to validate the hypothesis of Question 2a. At first, the data of Design 2a was standardized and seven outliers were found. Excluding them from the data set, a log transformation was performed on the remaining data which confirmed its normal distribution using both Skewness/kurtosis \( (s=0.9307, k=0.0690, p=0.1898) \) and Shapiro-Wilk \( (W=0.9939, V=1.732, p=0.0953) \) tests. Cook-Weisberg test revealed that the data sets were having constant variance \( (p=0.0608) \).

A repeated measures ANOVA was performed with peak luminance and relative luminance as independent variables and visibility threshold as dependent variable on the transformed data of Design 2a. It shows that the main effects of both the peak luminance \( F(1,409) = 15.17, p < 0.001, \eta^2_{\text{partial}} = 0.036 \) and relative luminance \( F(1,409) = 265.0, p < 0.001, \eta^2_{\text{partial}} = 0.393 \) are significant but their interaction is not \( F(1,409) = 0.03, p = 0.8595, \eta^2_{\text{partial}} = 0.0007 \). Hence, for this design, the relative luminance has a larger effect on the visibility threshold than the peak luminance. The adjusted significance level is \( (0.05/3) \) i.e. 0.0167.

An independent group t-test revealed that the visibility threshold at LPL \( (M=0.0088; SD=0.0063) \) is significantly higher than that at HPL \( (M=0.0071; SD=0.0046) \) \( (t(411)=3.05, p=0.002) \). Another independent t-test showed that the visibility threshold at RL1 \( (M=0.0118; SD=0.0061) \) is significantly higher than that at RL3 \( (M=0.0053; SD=0.0034) \) \( (t(411)=16.01, p<0.001) \) which is also seen in section 4.2.2.1.

As there was no interaction effect found between the peak luminance and the relative luminance levels on the visibility thresholds, no post hoc was performed to investigate their effects separately by keeping each other constant.

**Case 2: At constant absolute luminance**

This aimed to answer Question 2b. At first, the data of Design 2b was first standardized and seven outliers were found. Excluding them from the data set, a log transformation was performed on the remaining data which confirmed its normal distribution using both Skewness/kurtosis \( (s=0.4017, k=0.0592, p=0.1182) \) and Shapiro-Wilk \( (W=0.9935, V=1.833, p=0.0744) \) tests. Cook-Weisberg test revealed that the data sets were having constant variance \( (p=0.0713) \).
A repeated measures ANOVA was performed with peak luminance and absolute luminance as independent variables and visibility threshold as dependent variable on the transformed data of Design 2b. It shows that the main effect of the peak luminance \((F(1,409) = 5.8, p = 0.0165, \eta^2_{partial} = 0.014)\) is marginally significant, the main effect of the absolute luminance \((F(1,409) = 295.14, p < 0.001, \eta^2_{partial} = 0.419)\) is significant but their interaction is not significant \((F(1,409) = 0.1, p = 0.7523, \eta^2_{partial} = 0.0002)\). Hence, for this design, the absolute luminance has a larger effect on the visibility threshold than the peak luminance. The adjusted significance level is \((0.05/3)\) i.e. 0.0167.

An independent group t-test revealed that the visibility threshold at LPL \((M=0.0063; SD=0.0041)\) is not significantly different than that at HPL \((M=0.0071; SD=0.0046)\) \((t(411)=-1.88, p=0.06)\), even though the main effect of the peak luminance was found significant (marginally) in the ANOVA. Another independent t-test showed that the visibility threshold at AL2 \((M=0.0099; SD=0.0044)\) is significantly higher than that at AL4 \((M=0.0044; SD=0.0026); (t(411)=17.08, p<0.001)\).

Since, there was no interaction effect found between the peak luminance and the absolute luminance levels on the visibility thresholds, no post hoc was performed to investigate their effects separately by keeping each other constant.

![Figure 4.7](image)

**Figure 4.7** Visibility thresholds (with 95% confidence interval) for two different widths (two plots side by side) and three different chromaticity steepness levels (different marker type) as function of two different peak luminances (x-axis) at constant relative (different filling type for different RL) and absolute luminance values (different filling type for different AL) respectively. RL and AL are shown in different line types. Visibility thresholds are expressed as \(\Delta u'v'\); the widths impact the visibility thresholds for smooth steepness and at low relative luminance the most. This image is also present in Appendix 8.6 with a high resolution.

### 4.2.2.3 EFFECT OF WIDTH OF THE LUMINANCE PROFILE

To test the effect of width of the luminance profile on the visibility thresholds, the data were selected from Design 3. This test aimed to answer the Question 3. At first, the data of Design 3 was standardized and nine outliers were found. Excluding them from the data set, a log transformation was performed on the remaining data which confirmed its normal distribution using both Skewness/kurtosis \((s=0.6890, k=0.0857, p=0.2108)\) and Shapiro-Wilk \((W=0.9958, V=1.701, p=0.0988)\) tests. Cook-Weisberg test revealed that the data sets were having constant variance \((p=0.3705)\).

A repeated measures ANOVA was performed with width as independent variable and visibility threshold as dependent variable on the transformed data of Design 3. It shows that the main effect of the width \((F(1,618) = \)
4.2.2.4 EFFECT OF STEEPNESS OF THE CHROMATICITY TRANSITION

To test the effect of steepness of the chromaticity profile on the visibility thresholds, the data were selected from Design 4. This test aimed to validate the hypothesis of the Question 4. At first, the data of Design 4 was standardized and eight outliers were found. Excluding them from the data set, a log transformation was performed on the remaining data which confirmed its normal distribution using both Skewness/kurtosis ($s=0.3801$, $k=0.1524$, $p=0.2431$) and Shapiro-Wilk ($W=0.99045$, $V=2.453$, $p=0.0167$) tests. Unfortunately Cook-Weisberg test revealed that the data sets were not having constant variance ($p=0.0024$). Still, we considered to perform an ANOVA as discussed in the section 4.1.7.

A repeated measures ANOVA was performed with steepness and the combination of the peak luminance and the relative luminance as independent variables and visibility threshold as dependent variable on the transformed data of Design 4. It shows that the main effects of both the steepness ($F(2,361) = 59.48$, $p < 0.001$, $\eta^2_{\text{partial}} = 0.2478$) and the combination ($F(2,361) = 14.33$, $p < 0.001$, $\eta^2_{\text{partial}} = 0.0736$) are highly significant, although the steepness has a larger effect on the visibility threshold. However, their interaction is not found significant ($F(4,361) = 1.79$, $p = 0.1311$, $\eta^2_{\text{partial}} = 0.0194$). The adjusted significance level was $0.05/3 = 0.0167$.

Post hoc analyses (between three steepness pairs) were performed which revealed that the visibility threshold for the steepest chromaticity transition ($M=0.0032$, $SD=0.0012$) is significantly lower than that for the chromaticity transition of medium steepness ($M=0.0045$, $SD=0.0023$) ($t(244) = -4.72$, $p < 0.001$) and the visibility threshold for the medium steep chromaticity transition is also significantly lower than that for the smoothest chromaticity transition ($M=0.0068$, $SD=0.004$) ($t(246) = -5.84$, $p < 0.001$). The adjusted significance level was $0.05/3 = 0.0167$. 

Figure 4.8 shows the plot of visibility thresholds along with their 95% confidence interval for only those combinations of peak luminance and the relative luminance where all three steepness levels were measured.
Another post hoc analyses investigated that the visibility threshold measured at RL3 (M=0.0053, SD=0.0034) is significantly higher than that at RL4 (M=0.0041, SD=0.0022) \(t(245) = 4.77, p < 0.001\) when the peak luminance is fixed at LPL. We already have seen this result in section 4.2.2.1 but that was measured for only two steepness levels at those relative luminance values. At RL3, when the relative luminance stays constant, decreasing the peak luminance resulted in higher visibility thresholds, though a marginally significant \(t(245) = 2.81, p = 0.016\) only. At AL4, when the absolute luminance stays constant, changing the peak luminance did not affect the visibility thresholds.

### 4.2.2.5 EFFECT OF PRESENTATION MODE

To test the effect of the presentation mode on the visibility thresholds, the data were selected from Design 5. This test aimed to validate the hypothesis of Question 5. At first, the data of Design 5 was standardized and nine outliers were found. Excluding them from the data set, a log transformation was performed on the remaining data which increases the normality, even though Skewness/kurtosis \(s=0.8948, k=0.0004, p=0.0042\) and Shapiro-Wilk \(W=0.97077, V=5.208, p<0.001\) tests rejected the normality assumption. An ANOVA was still considered to perform and the reason is already discussed in section 4.1.7.

In Figure 4.9, we see that the visibility threshold is lower when a reference spot is present. The difference in the visibility thresholds seems to be related to the steepness of the chromaticity transition, such that the smoother transitions lead to the higher thresholds differences between the two presentation modes.

![Figure 4.9: Visibility thresholds](image)

**Figure 4.9** Visibility thresholds (with 95% confidence interval) for two different widths of the luminance profile (two plots side by side) and three different steepness levels (different marker types) as function of two different presentation modes (x-axis); visibility thresholds are expressed as \(\Delta u'v'\).

A repeated measures ANOVA was performed with presentation mode as independent variable and visibility threshold as dependent variable on the transformed data of Design 5. It shows that the main effect of the presentation mode \(F(1,243) = 36.12, p < 0.001, \eta^2_{\text{partial}} = 0.1294\) is highly significant, along with having a large effect on the visibility threshold. As mentioned in the design, due to the violation of the normality assumption even after the transformation, a further Kruskal-Wallis test was also performed to cross-validate the outcome of the ANOVA, which also resulted a significant main effect of the presentation mode on the visibility threshold \(\chi^2(1)=29.987, p<0.001\).

An independent group t-test revealed that the visibility threshold for ‘without reference’ presentation mode (M=0.0106, SD=0.0067) is significantly higher (almost twice) than that for ‘with reference’ presentation mode (M=0.0057, SD=0.0033) \(t(243) = 6.01, p < 0.001\).
4.2.2.6 SUMMARY OF THE RESULTS

For a standard Gaussian luminance profile, the visibility of the CoA effect was found to significantly depend on 1) the position of that color change in the luminance profile, 2) the peak luminance, 3) the width of the luminance profile and 4) the steepness of the CoA. In addition, the CoA effect is more easily detected when a reference spot (without any color transition) is present along with the target spot.

The CoA effect in the luminance profile is less well detected when the color transition occurs more towards the edge of the spot. Besides, the visibility threshold increases when the peak luminance is lower. However, at constant absolute luminance values, varying the peak luminance levels does not change the visibility threshold whereas at constant relative luminance, low peak luminance level results in higher thresholds. Also, a wider luminance profile makes the CoA effect less visible.

Furthermore, the color change is less well detected if the steepness becomes more gradual. The visibility of a CoA effect is much more sensitive (by a factor of 2) if it is compared to a reference spot simultaneously.
5 GENERAL DISCUSSION

In this section several noteworthy findings and previously formed hypotheses from the experimental results are discussed.

5.1 DISCUSSION ON THE EFFECT OF POSITION IN THE SPOT

The hypothesis of Question 1 states: \textit{the visibility threshold of a gradual CoA in a spot with a Gaussian luminance profile is increased if the position of the chromaticity profile is more towards the edge of the spot.}

Keeping the peak luminance constant, changing the position of the color transition in a spot changes both absolute and relative luminance. In section 4.2.2.1, we saw that the further the color transition occurs towards the edge of the spot (i.e. at both lower relative and absolute luminance), the more difficult it is to see that color transition. This validates the hypothesis of the Question 1, which I in line with the results of Lambooij (2015)'s study. Noteworthy is that the rate of growth in the visibility thresholds between the positions at the edge of the spot were seen much higher than that between the positions at relatively towards its center.

5.2 DISCUSSION ON THE EFFECT OF PEAK LUMINANCE OF THE LUMINANCE PROFILE

The effect of the peak luminance is examined for two different (Question 2a and 2b) cases, such that when the relative luminance is constant and varying absolute luminance, or vice versa.

The hypothesis of Question 2a states: \textit{the visibility threshold of a gradual CoA in a spot with a Gaussian luminance profile is increased if the peak luminance is decreased while keeping the relative luminance constant, but the absolute luminance changes.}

In section 4.2.2.2, we saw that the color transition at the low peak luminance level is less perceivable when the relative luminance at its position in the luminance profile is constant. This validates the hypothesis of the Question 2a which is in line with Kim et al. (2013)'s study. They also found similar results even though their experimental stimuli and setup was quite different from ours. They used iso-luminous chromatic gratings which means that both the relative and absolute luminance of each point of the stimulus image was equal and constant. They observed a significant decrement in the visibility threshold with increasing the luminance level until a certain point (2 cd/m²) above which the threshold stabilizes. Figure 5.1 shows the chromatic contrast threshold curve of one chromatic grating (green to red) used in Kim’s experiment (using rigid line) and also the visibility thresholds measured at four different absolute luminance values in our result, averaged across the widths of the luminance profile and the participants (in dashed line). Both are presented in log₁₀ scale.

To compare with Kim’s results, we converted the visual angle of the color transition into respective spatial frequencies (but only for half a cycle symmetrically) and arrived at spatial frequencies 0.055, 0.175 and 1 cpd for steepness levels of 9°, 2.8° and 0.5° respectively. However, most of these local absolute luminance fall in the mesopic range of vision (Ferwerda et al., 1996) although the center of the spot is undoubtedly photopic.
Figure 5.1 Contrast thresholds (in $\log_{10}$ scale) are plotted at nine different absolute luminance levels (rigid line for Kim’s data and dashed line for our result) as function of eight different spatial frequencies (six for Kim’s data and three for our result). Figure 4 in Kim et al. (2013) is replotted with contrast threshold as y-axis; contrast thresholds in Kim’s study were calculated using the relative modulations ($\Delta L/L$, $\Delta M/M$ and $\Delta S/S$) of the iso-luminous red-green grating along LMS dimensions of the LMS color space (with respect to the background color) and the visibility thresholds in our data, expressed as $\Delta u'v'$. Note how thresholds decrease with increasing luminance level in both the studies, but saturates somewhere between 2 and 40 cd/m$^2$ in Kim’s data.

The lowest spatial frequency (0.055 cpd) used in our experiment is substantially smaller than Kim’s (0.25 cpd). Since, we observed that the main effect of the peak luminance is highly significant on the visibility threshold with moderate to high effect size, provided the relative luminance is constant (see section 4.2.2.2), the visibility threshold is found to decrease with increasing peak luminance. Hence, in our data, the visibility thresholds never saturates for the tested local absolute luminance values (0.7 to 10 cd/m$^2$). It is unclear in Kim’s data, at what exact value of the luminance (absolute) level, the saturation starts. Therefore, to be in line with Kim’s findings, we might conclude that the saturation in visibility thresholds does not happen below 10 cd/m$^2$ luminance value. Having low absolute luminance values at the color transition in a Gaussian shaped luminance profile, we might have a local adaptation in our experiment unlike a global adaptation seen everywhere in Kim’s experiment. However, both the studies (Kim’s and ours) differ in the properties of stimuli, setup as well as in methodologies. Also, the number of visible cycles might have a differentiating effect on the visibility threshold between them.

The Question 2b explores: how is the visibility threshold of a gradual change in the chromaticity of a spot light affected by the peak luminance, while keeping the absolute luminance at the position of the chromaticity profile constant.

Unlike the outcomes at constant relative luminance values, the visibility did not get impacted by changing the peak luminance levels when the color transition was tested at constant absolute luminance values in the luminance profile.

Noteworthy is that the effect of the peak luminance on the visibility thresholds was not found to depend on where the color transition occurs in the spot.
5.3 DISCUSSION ON THE EFFECT OF WIDTH OF THE LUMINANCE PROFILE

The Question 3 explores: how is the visibility threshold of a gradual CoA in a spot with a Gaussian luminance profile affected by the width of the luminance profile, while both relative and absolute luminances are constant but the position is changed?

In section 4.2.2.3, we saw that a wider luminance profile makes the CoA effect less visible which answers the Question 3. Mullen et al. (2014) observed that the detection of a chromatic grating is influenced by the spatial frequency of the luminance profile of the grating. It is to be noted that both the spatial frequency of a luminance grating and the width of a Gaussian luminance profile give information about the gradient or slope of the change in luminance. They found that the color change was less visible for a higher spatial frequency of luminance grating. Generally, the condensed nature of a higher spatial frequency gradually shrinks down the width of a particular cycle in that sinusoid. So, according to their findings, the visibility thresholds in our experiment should have been lower if the slope of the luminance profile is lower i.e. the width is larger. But we see exactly the opposite behavior (at least for the lower peak luminance). Needless to mention that in the pilot experiment, we found that a Uniform luminance profile results in much lower visibility thresholds than the wide luminance (width = 11.2°) profile, which backs the findings of Mullen’s research. From this, we may conclude that the visibility threshold increases with the width of the luminance profile until a certain point and then decreases which eventually results in much lower thresholds for the uniform luminance profile. However, the outcomes of Mullen et al. (2014) might be affected by the temporal frequencies too, they used along with the spatial frequencies, which is not the case in our experiment.

5.4 DISCUSSION ON THE EFFECT OF STEEPNESS OF THE CHROMATICITY PROFILE

The hypothesis of Question 4 states: The visibility threshold of a gradual CoA in a spot with a Gaussian luminance profile is increased if the chromaticity transition is more gradual.

In section 4.2.2.4, we saw that the smoother the color transition in the spot is, the more difficult it is to detect, which validates the hypothesis of Question 4. The finding is in line with Vogels & Lambooij (2014)’s study, although they tested with an iso-luminous chromatic grating. They observed that below 0.3 cpd, the visibility threshold increases with decreasing spatial frequency. Needless to mention that the number of visible cycles was low below 0.3 cpd as the grating area was fixed. In contrast, we dealt with even lower spatial frequencies (0.055 and 0.175 cpd) than 0.3 cpd and with only half a cycle (symmetrically) visible in our stimuli. Figure 5.2 compares the visibility thresholds between Vogels & Lambooij (2014) and our study with nine different spatial frequencies. Our result shows a sharp decline in the visibility thresholds with increasing the spatial frequency. As the number of visible cycle was always fixed in our experiment, the pattern of the visibility threshold function is different from that of Vogels & Lambooij (2014), where the number of visible cycle always changed with changing the spatial frequency. The increment in the visibility thresholds for the smoother color change could be because a gradual change in color tends to yield weaker responses as it fails to excite the corresponding receptive field center strongly like a steeper color change does (Shapley et al, 2002). Averaging across the widths of the luminance profile, the effect of the steepness on the visibility thresholds was not found significantly different for any of the cases such as 1) when only the absolute luminance is constant, 2) when only the relative luminance is constant, and 3) when only the peak luminance is constant. However, Figure 4.8 indicates that the width of the luminance profile might influence the effect of the smoothest color transition on the visibility thresholds when tested either at a constant relative luminance value or at a constant peak luminance level.
5.5 DISCUSSION ON THE EFFECT OF PRESENTATION MODE

The hypothesis of Question 5 states: *The visibility threshold of a gradual CoA in a spot with a Gaussian luminance profile is increased if the color profile is presented without a reference stimulus compared to with a reference stimulus.*

It seems more realistic to select and buy a light source or luminaire without visually comparing it to an “ideal” one. In section 4.2.2.5, we saw that our participants were much more sensitive (almost a factor of 2) when the target spot was compared to a reference spot without having any color change, which validates the hypothesis of Question 5. The result supports the observation by Rosenberger et al. (2012). Besides, Figure 4.9 indicates that the width of the luminance profile might also influence the visibility of CoA effect in the absence of a reference spot, especially with smoother color transitions. Needless to mention that comparing a spot with CoA effect to a reference spot is more scientifically reliable, although it depends on the objective. Without any reference might result in a higher variance due to the subjective evaluation by participants. We can also use the visibility thresholds that are measured with reference and apply those while designing a LED spot, because at that visibility thresholds, we should not see any CoA effect even if we do not compare the spot to any reference.

5.6 DISCUSSION ON CHROMATIC ADAPTATION

Chromatic adaptation (between participants) was also a concern during the design of the experiment. Especially at small color differences (Δu’v’), if participants spend different amounts of time viewing the images, they will have different amounts of chromatic adaptation which could affect the visibility thresholds (Fairchild & Reniff, 1997), although that adaptation happens slightly slower if luminance changes are also involved (Hunt, 1950). We hence decided to minimize the inter-distance (visual angle = 1.5°) between test and reference stimuli so that they spend minimal time for eye saccades. We also recorded the time to complete each of the 36 staircases (conditions) for each participant from which we found that they spent around 4 secs per step size on average for each condition. Assuming that the comparison between test and reference stimuli made them to do at least 2 saccades, i.e. once on test and another on reference stimuli before taking a decision, hence the average time taken at each of the stimuli is 2 secs per step. According to Fairchild & Reniff (1977), for that much time spent, the proportion of chromatic adaptation is not that high (around 20%). However, the chance of chromatic
adaption was found much higher while testing without reference as the participants spent longer time to detect a color transition.

5.7 FUTURE RESEARCH

A suggestion for future research would be to work towards measuring more dependencies between chromaticity and luminance information in a spot. Also, some further work should be carried out at higher peak luminances (such as > 300 cd/m²) to see how the sensitivity behaves at high brightness. As the interaction effect between the peak luminance levels and either relative or absolute luminance values was not found significant, the color transitions should further be tested keeping more distance between each other in the luminance profile to confirm on the non-significance. The effect of widths of the luminance profile on the visibility threshold should also be further analyzed taking more variations in steepness of the color transition and the relative luminance values. The effect of base color is not included in the current study which can also be taken into consideration in future as Vogels & Lambooij (2014) observed that base color with higher CCT is less sensitive. Besides, the methodology for ‘no reference’ should be improved. The reason is that, during the training, few participants doubted that there was always a color change in the target stimuli even if the there was no physical color difference present. The reason is that they tended to confuse between the differences in luminance intensity in the spot which they most possibly perceived as a plausible color change.

6 CONCLUSIONS

This study investigated that the visibility of a color-over-angle (CoA) effect in a simulated LED spot depends on several lighting parameters such as the peak luminance and the width of a Gaussian luminance profile, the steepness and position of a chromaticity transition in the spot. The less sensitive the users are towards a color-over-angle effect for any condition (combinations of the lighting parameters), the better it is to use that condition when designing a LED spot light. In that way, it is a cost effective solution as some color non-uniformities can be ignored in the spot as far as they are less likely to be perceived by the users. A significant effect of the peak luminance on the visibility thresholds is observed when measured at constant relative luminance values, which is not the case when measured at constant absolute luminance values. Hence, when designing a LED spot with a different peak luminance from a current specification, the position of the non-perceivable color transition should be adjusted so that it contains at least the same or lower absolute luminance value in the new luminance profile. A wider luminance profile is also preferable to decrease the chance of detecting CoA effect in the spot. Same goes for a color transition with a gradual change. Also, the visibility of the CoA effect in a LED spot increases by almost a factor of 2 in presence of an ‘ideal’ reference spot. The visibility thresholds measured in the presence of a reference spot are preferable while designing spots because they can make sure that the detection of the color change is difficult in both presence and absence of a reference spot.
REFERENCES


Optoelectronics Industry Development Association (2001). THE PROMISE OF SOLID STATE LIGHTING FOR GENERAL ILLUMINATION.


8 APPENDICES

8.1 VARIABLE DEFINITIONS

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1. **Visibility threshold**: The Euclidean distance between the coordinates of two color points \([u_1', v_1'] \) & \([u_2', v_2'] \) in 1976 CIE \(u'v'\) is used as visibility thresholds such that:

\[
\Delta u'v' = \sqrt{(u'_1 - u'_2)^2 + (v'_1 - v'_2)^2}
\]

2. **Peak luminance level**: The maximum or the peak value of a Gaussian luminance function expressed in cd/m\(^2\). For example, the point (black colored) at position \(P_1\) in the Figure 8.1 indicates the peak value of that function.

Let’s say, the peak luminance = 154 cd/m\(^2\). Now, if the point (red colored) at position \(P_2\) contains absolute luminance exactly half of the maximum value (such as 77 cd/m\(^2\)), we call it as full width at half maximum (FWHM) of the Gaussian function. Besides, if another point (blue colored) at position \(P_3\) in the Gaussian luminance profile has absolute luminance value = 10 cd/m\(^2\), the relative luminance (=absolute luminance at that position/peak luminance) at that position will be (=10/154) around 0.07. Hence the relative luminance at FWHM is always 0.5.

![Figure 8.1 A Gaussian luminance profile with points representing peak luminance, relative & absolute luminance](image-url)
3. **Width of a luminance profile:** The width of the luminance profile is represented by the visual angle of the FWHM of that Gaussian shaped profile. Different FWHM values give different rate of changes (gradients) in luminance values if the peak luminance is kept constant.

4. **Steepness of a chromaticity profile:** The reciprocal of the width of the chromaticity (color) transition indicates its steepness. It is also expressed in visual angles ($\theta$ in Figure 8.2). Figure 8.2 explains what steepness means in the study. Lesser the angle $\theta$, steeper the color change and vice versa. For easy understanding, we used steepness and the visual angle of the chromaticity transition interchangeably whereas in actual, they are reciprocal to each other.

![Figure 8.2](image)

**Figure 8.2** Steepness of the chromaticity profile in a simulated LED spot is represented as the visual angle of the color change.

5. **Position of a chromaticity profile in the spot:** The position of chromaticity profile is indicated by the relative luminance at that position.

6. **Presentation mode:** Two types of presentation modes: 1) the spot with chromaticity transition is compared to a reference spot where there is no chromaticity transition. 2) the spot with chromaticity transition is evaluated without comparing to any reference.
8.2 EXPERIMENTAL CONDITIONS

All 30 conditions (with reference stimuli) are pictorially presented. Among which the conditions highlighted in grey are repeated without reference stimuli is shown (6 conditions in total).

The conditions are simplified in below Table.
<table>
<thead>
<tr>
<th></th>
<th>Angle</th>
<th>Posts</th>
<th>Force</th>
<th>0.5°</th>
<th></th>
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<tbody>
<tr>
<td>16</td>
<td>5.6°</td>
<td>77</td>
<td>0.065</td>
<td>5</td>
<td>0.5° no</td>
</tr>
<tr>
<td>17</td>
<td>5.6°</td>
<td>77</td>
<td>0.065</td>
<td>5</td>
<td>2.8° no</td>
</tr>
<tr>
<td>18</td>
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<td>77</td>
<td>0.065</td>
<td>5</td>
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<tr>
<td>19</td>
<td>11.2°</td>
<td>154</td>
<td>0.009</td>
<td>1.4</td>
<td>0.5° yes</td>
</tr>
<tr>
<td>20</td>
<td>11.2°</td>
<td>154</td>
<td>0.009</td>
<td>1.4</td>
<td>2.8° yes</td>
</tr>
<tr>
<td>21</td>
<td>11.2°</td>
<td>154</td>
<td>0.065</td>
<td>10</td>
<td>0.5° yes</td>
</tr>
<tr>
<td>22</td>
<td>11.2°</td>
<td>154</td>
<td>0.065</td>
<td>10</td>
<td>2.8° yes</td>
</tr>
<tr>
<td>23</td>
<td>11.2°</td>
<td>154</td>
<td>0.065</td>
<td>10</td>
<td>9° yes</td>
</tr>
<tr>
<td>24</td>
<td>11.2°</td>
<td>77</td>
<td>0.009</td>
<td>0.7</td>
<td>0.5° yes</td>
</tr>
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<td>11.2°</td>
<td>77</td>
<td>0.009</td>
<td>0.7</td>
<td>2.8° yes</td>
</tr>
<tr>
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<td>77</td>
<td>0.018</td>
<td>1.4</td>
<td>0.5° yes</td>
</tr>
<tr>
<td>27</td>
<td>11.2°</td>
<td>77</td>
<td>0.018</td>
<td>1.4</td>
<td>2.8° yes</td>
</tr>
<tr>
<td>28</td>
<td>11.2°</td>
<td>77</td>
<td>0.065</td>
<td>5</td>
<td>0.5° yes</td>
</tr>
<tr>
<td>29</td>
<td>11.2°</td>
<td>77</td>
<td>0.065</td>
<td>5</td>
<td>2.8° yes</td>
</tr>
<tr>
<td>30</td>
<td>11.2°</td>
<td>77</td>
<td>0.065</td>
<td>5</td>
<td>9° yes</td>
</tr>
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<td>31</td>
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<td>0.13</td>
<td>10</td>
<td>0.5° yes</td>
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<td>0.13</td>
<td>10</td>
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<td>10</td>
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<tr>
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<td>11.2°</td>
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<td>0.065</td>
<td>5</td>
<td>0.5° no</td>
</tr>
<tr>
<td>35</td>
<td>11.2°</td>
<td>77</td>
<td>0.065</td>
<td>5</td>
<td>2.8° no</td>
</tr>
<tr>
<td>36</td>
<td>11.2°</td>
<td>77</td>
<td>0.065</td>
<td>5</td>
<td>9° no</td>
</tr>
</tbody>
</table>
### 8.3 RANGE OF MAXIMUM COLOR DIFFERENCES PER CONDITION (USED IN STAIRCASE)

<table>
<thead>
<tr>
<th>Condition</th>
<th>maximum color differences (along with step size)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0-0.003 Δu’v’ (0.0001Δu’v’); 0.0031-0.015 Δu’v’ (0.00012Δu’v’); 0.016-0.06 Δu’v’ (0.0022Δu’v’)</td>
</tr>
<tr>
<td>2</td>
<td>0.005-0.025 (0.0002Δu’v’); 0.026-0.06 Δu’v’ (0.0017Δu’v’)</td>
</tr>
<tr>
<td>3</td>
<td>0-0.01 Δu’v’ (0.0001Δu’v’); 0.011-0.06 Δu’v’ (0.00245Δu’v’)</td>
</tr>
<tr>
<td>4</td>
<td>0-0.003 Δu’v’ (0.0001Δu’v’); 0.0031-0.015 Δu’v’ (0.00012Δu’v’); 0.016-0.06 Δu’v’ (0.0022Δu’v’)</td>
</tr>
<tr>
<td>5</td>
<td>0-0.003 Δu’v’ (0.0001Δu’v’); 0.0031-0.015 Δu’v’ (0.00012Δu’v’); 0.016-0.06 Δu’v’ (0.0022Δu’v’)</td>
</tr>
<tr>
<td>6</td>
<td>0-0.003 Δu’v’ (0.0001Δu’v’); 0.0031-0.015 Δu’v’ (0.00012Δu’v’); 0.016-0.06 Δu’v’ (0.0022Δu’v’)</td>
</tr>
<tr>
<td>7</td>
<td>0.005-0.008 Δu’v’ (0.0001Δu’v’); 0.0081-0.03 Δu’v’ (0.00022Δu’v’); 0.031-0.06 Δu’v’ (0.00145Δu’v’)</td>
</tr>
<tr>
<td>8</td>
<td>0-0.003 Δu’v’ (0.0001Δu’v’); 0.0031-0.015 Δu’v’ (0.00012Δu’v’); 0.016-0.06 Δu’v’ (0.0022Δu’v’)</td>
</tr>
<tr>
<td>9</td>
<td>0.005-0.025 (0.0002Δu’v’); 0.026-0.06 Δu’v’ (0.0017Δu’v’)</td>
</tr>
<tr>
<td>10</td>
<td>0-0.01 Δu’v’ (0.0001Δu’v’); 0.011-0.06 Δu’v’ (0.00245Δu’v’)</td>
</tr>
<tr>
<td>11</td>
<td>0-0.003 Δu’v’ (0.0001Δu’v’); 0.0031-0.015 Δu’v’ (0.00012Δu’v’); 0.016-0.06 Δu’v’ (0.0022Δu’v’)</td>
</tr>
<tr>
<td>12</td>
<td>0-0.003 Δu’v’ (0.0001Δu’v’); 0.0031-0.015 Δu’v’ (0.00012Δu’v’); 0.016-0.06 Δu’v’ (0.0022Δu’v’)</td>
</tr>
<tr>
<td>13</td>
<td>0-0.01 Δu’v’ (0.0001Δu’v’); 0.011-0.06 Δu’v’ (0.00245Δu’v’)</td>
</tr>
<tr>
<td>14</td>
<td>0-0.01 Δu’v’ (0.0001Δu’v’); 0.011-0.06 Δu’v’ (0.00245Δu’v’)</td>
</tr>
<tr>
<td>15</td>
<td>0-0.003 Δu’v’ (0.0001Δu’v’); 0.0031-0.015 Δu’v’ (0.00012Δu’v’); 0.016-0.06 Δu’v’ (0.0022Δu’v’)</td>
</tr>
<tr>
<td>16</td>
<td>0-0.01 Δu’v’ (0.0001Δu’v’); 0.011-0.06 Δu’v’ (0.00245Δu’v’)</td>
</tr>
<tr>
<td>17</td>
<td>0-0.003 Δu’v’ (0.0001Δu’v’); 0.0031-0.015 Δu’v’ (0.00012Δu’v’); 0.016-0.06 Δu’v’ (0.0022Δu’v’)</td>
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<td>0-0.003 Δu’v’ (0.0001Δu’v’); 0.0031-0.015 Δu’v’ (0.00012Δu’v’); 0.016-0.06 Δu’v’ (0.0022Δu’v’)</td>
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<td>0-0.003 Δu’v’ (0.0001Δu’v’); 0.0031-0.015 Δu’v’ (0.00012Δu’v’); 0.016-0.06 Δu’v’ (0.0022Δu’v’)</td>
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<td>22</td>
<td>0-0.01 Δu’v’ (0.0001Δu’v’); 0.011-0.06 Δu’v’ (0.00245Δu’v’)</td>
</tr>
<tr>
<td>23</td>
<td>0-0.003 Δu’v’ (0.0001Δu’v’); 0.0031-0.015 Δu’v’ (0.00012Δu’v’); 0.016-0.06 Δu’v’ (0.0022Δu’v’)</td>
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<td>24</td>
<td>0-0.003 Δu’v’ (0.0001Δu’v’); 0.0031-0.015 Δu’v’ (0.00012Δu’v’); 0.016-0.06 Δu’v’ (0.0022Δu’v’)</td>
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<td>25</td>
<td>0.005-0.008 Δu’v’ (0.0001Δu’v’); 0.0081-0.03 Δu’v’ (0.00022Δu’v’); 0.031-0.06 Δu’v’ (0.00145Δu’v’)</td>
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</tr>
<tr>
<td>29</td>
<td>0-0.01 Δu’v’ (0.0001Δu’v’); 0.011-0.06 Δu’v’ (0.00245Δu’v’)</td>
</tr>
<tr>
<td>30</td>
<td>0-0.004 Δu’v’ (0.0001Δu’v’); 0.0041-0.02 Δu’v’ (0.00016Δu’v’); 0.021-0.06 Δu’v’ (0.00195Δu’v’)</td>
</tr>
<tr>
<td>31</td>
<td>0-0.01 Δu’v’ (0.0001Δu’v’); 0.011-0.06 Δu’v’ (0.00245Δu’v’)</td>
</tr>
<tr>
<td>32</td>
<td>0-0.01 Δu’v’ (0.0001Δu’v’); 0.011-0.06 Δu’v’ (0.00245Δu’v’)</td>
</tr>
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<td>33</td>
<td>0-0.003 Δu’v’ (0.0001Δu’v’); 0.0031-0.015 Δu’v’ (0.00012Δu’v’); 0.016-0.06 Δu’v’ (0.0022Δu’v’)</td>
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<tr>
<td>34</td>
<td>0-0.01 Δu’v’ (0.0001Δu’v’); 0.011-0.06 Δu’v’ (0.00245Δu’v’)</td>
</tr>
<tr>
<td>35</td>
<td>0-0.01 Δu’v’ (0.0001Δu’v’); 0.011-0.06 Δu’v’ (0.00245Δu’v’)</td>
</tr>
<tr>
<td>36</td>
<td>0-0.004 Δu’v’ (0.0001Δu’v’); 0.0041-0.02 Δu’v’ (0.00016Δu’v’); 0.021-0.06 Δu’v’ (0.00195Δu’v’)</td>
</tr>
</tbody>
</table>
8.4 BRIEFING THE EXPERIMENT

The text below is the verbal explanation given to the participants prior to the 1st session experiment. The briefing is followed by a training with few demo images for 2 mins.

Welcome and thank you for participating in my experiment. We will start with a short color-blindness test. As you were informed in advance that there will be 3 different sessions, for about half an hour each. I am investigating visibility thresholds of color-over-angle effect in a simulated LED spot lights. In two of sessions, you will see three series of images coming one after other. And rest will have only two series of images. You will see two different kind of images displayed on the screen: one has two spot lights appearing simultaneously side by side in which one of them has a color change along with change in the intensity whereas the other will have a uniform color but only change in intensity. You have to indicate which one you think has a color change. Indicate by pressing left / right keystroke based on its respective location on the monitor. The other kind of images will have only one spot with possibility of color change. You will have to indicate if you see any color change by pressing left / right keystroke for no/yes respectively. You will always be starting with seeing a clear color change in one of the spots. Gradually, the difference between those two colors would be decreased so that at some point of time you will find difficulties to either discriminate between those two when reference is present or detect any color change when only one spot is there. If this happens, please make a guess after a thorough scanning on them. One recommendation is that please start looking from the center of the spot and go gradually towards the edge of the spot if you do not find any color change clearly. Please respond to each image as quick as possible. In each of sessions, each series starts with a uniform adaptation image for 10 secs. You will have to sit in a chinrest and look at the screen for that duration. You will have to sit like this for the entire experiment. After each series of images, you will again see a uniform adaptation image for 10 secs before starting with the next series. This will repeat for 3 times or 2 times based on the session. Before starting with the experiment, you will also be trained with few demo images under the experimental setup to get an idea what to look for in the monitor and clarify your doubts if any.
8.5 INFORMED CONSENT

This document gives you information about the study “Visibility of color over angle for various luminance profiles”. Before the study begins, it is important that you learn about the procedure followed in this study and that you give your informed consent for voluntary participation. Please read this document carefully.

Aim and benefit of the study

The aim of this study is to measure the visibility threshold of a gradual change in chromaticity for LED spots. This information is used to contribute to the betterment of lighting technology without compromising on quality and price.

This study is done by Suvadeep Mukherjee, a student under the supervision of Dr. Ingrid Vogels of the Human-Technology Interaction group.

Procedure

The experiment will be carried out in 3 different sessions (same day or any other day based on participant’s availability). In each session, there will be 2 parts. In the first part, there will be two closely-situated simulated spots visible in the computer screen in horizontal fashion. In one of them, you will see a color variation (yellow or brown colored ring surrounding by a blueish white color filled circle). And the other won’t have any kind of color variations. You will have to notify which of them is having unwanted color variation by pressing left or right keystroke in a normal keyboard. In the other part, there will be only one spot visible in the screen. You will have to notify if you see any color variations (subjective assessment) based on the experience that you gained in the first part by pressing left (NO) or right (YES) keystroke. The same procedure will be repeated in other sessions too.

You will be sit in a chinrest close to (at 50 cm) monitor in a dark room. Before the experiment, you will be trained with some demo images so that you can practice beforehand. Before each part of each sessions get started, you will have to look at an iso-luminous image displayed on the screen for 10 sec and for 1.5 sec after each stimuli (image) is being displayed. During that time, you do not press anything, all you have to do is to look at them. There will be a series of images to be shown one after other, based on your inputs we will measure the visibility threshold of color over angle.

Risks

The study does not involve any risks or detrimental side effects.

Duration

The study will last approximately 30 minutes (each of 3 sessions).

Participants

You were selected because you are either a working professional or a student at Philips research Eindhoven.

Voluntary

Your participation is completely voluntary. You can refuse to participate without giving any reasons and you can stop your participation at any time during the study. You can also withdraw your permission to use your experimental data up to 24 hours after the study is finished. All this will have no negative consequences whatsoever.

Compensation

You will be compensated with candy bars.
Confidentiality

All research conducted at the Human-Technology Interaction Group adheres to the Code of Ethics of the NIP (Nederlands Instituut voor Psychologen – Dutch Institute for Psychologists).

We will not be sharing personal information about you to anyone outside of the research team. No video or audio recordings are made that could identify you. The information that we collect from this study is used for writing scientific publications and will be reported at group level. It will be completely anonymous and it cannot be traced back to you. Only the researchers will know your identity and we will lock that information up with a lock and key.

Further information

If you want more information about this study you can ask Suvadeep Mukherjee (contact email: suvadeep.mukherjee@philips.com).

If you have any complaints about this study, please contact the supervisor, Dr. Marc Lambooij (marc.lambooij@philips.com).

Certificate of Consent

I, (NAME).................................................. have read and understood this consent form and have been given the opportunity to ask questions. I agree to voluntary participate in this research study carried by the research group Human Technology Interaction of the Eindhoven University of Technology.

________________________________________  ______________________________
Participant’s Signature            Date

Participant’s paraph _____
8.6 HIGH RESOLUTION IMAGES FROM RESULT SECTION

**FIG 4.6**
WIDTH OF LUMINANCE PROFILE = LW (11.2°)

**FIG 4.7**
WIDTH OF LUMINANCE PROFILE = LW (11.2°)

**FIG 4.6**
WIDTH OF LUMINANCE PROFILE = LW (5.6°)

**FIG 4.7**
WIDTH OF LUMINANCE PROFILE = LW (5.6°)