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Flicker perception in the periphery

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Preface

I come from Poland. Several months ago I came to Eindhoven to do my studies. I followed master programme Human-Technology Interaction at the Eindhoven University of Technology. In the last phase of this study I joined Philips Research, the group of Visual Experiences, where I completed my graduation project. This report is a result of this project. I would like to thank all the people who contributed to this work. First, I'd like to thank my awesome supervisors, Dragan Sekulovski from Philips Research and Raymond Cuijpers and Yvonne de Kort from TU/e. Without your great support and inspiring ideas I wouldn't be able to complete this research. Further, special thanks to the entire Visual Experience group for the very warm atmosphere and a patience with looking at this not-that-pleasant flickering light. I'd like to thank Tin de Zeeuw, who was always there and listened to whatever I had to say (and for helping me through the labyrinth of HTC); to Alfredo Grunwald and all the internees who made my stay at Philips such a pleasure. Finally, I'd like to thank my best-in-the-world parents for being the best parents in the world.

Summary

In recent years LEDs (Light Emitting Diodes) began to play an important role in various lighting applications. LEDs, contrary to conventional analogue lights, can easily generate and change a wide range of chromaticites and brightness levels over time. This dynamic capability is a great advantage, but an issue of control may appear at this point. The light change can namely produce effects, which are unattractive and undesirable to people. Flicker is one example of such effects. It is defined as a repeated and quick light alternation, as opposite to a steady light. To prevent LEDs from flickering in an economical way, visibility thresholds have to be known. Visibility thresholds are defined as the largest amplitudes (the distance in change between two colors) for a particular set of parameters that produce steady and not flickering light changes. Previous studies already defined flicker visibility thresholds in human central vision Sekulovski (2007). However, LED-based lighting application can be extended into the periphery, so that they become even more useful and attractive. Human central vision differs from peripheral vision and therefore a new research was required. The goal of this study was to investigate human flicker sensitivity in peripheral vision under mental load. Mental load was introduced because peripheral light is hardly ever the main focus of attention.

Three experiments were conducted. In the first one human flicker sensitivity at different eccentricities was investigated. The second and third experiments served as a control tests for the first one. In the second experiment the effect of mental load on flicker perception was investigated. In the third experiment flicker sensitivity in the periphery was compared against sensitivity in central vision. Detection procedure was used in all three experiments.

The stimuli were defined within CIE LCh color space. The color was varied around one of the three base-color points: red, green or blue, and along one of the directions: Lightness, Chroma or hue. Five frequencies were used: 5Hz, 10Hz, 20Hz, 40Hz and 60Hz. Five different amplitudes were used; they differed across stimuli and were defined after pilot tests. Finally, three eccentricities were tested: 35deg, 60deg and 90deg. Threshold was measured in ΔE; 1ΔE is the smallest perceivable distance between two colors within the CIE LCh color space.

In the first experiment it was found that Chroma and hue flicker sensitivity gets impaired with the increasing eccentricities for all the frequencies used in this study. Lightness flicker sensitivity gets impaired but only at high frequencies (<20Hz); for low frequencies (5Hz and 10Hz), due to the speed at which signal is modulated by rods, lightness flicker sensitivity increases with the increasing eccentricity. Lightness flicker was also found to be independent of the base-color point at every frequency and eccentricity. Lightness flicker peaks at 10hz for 35 and 60 deg, whereas in the far periphery (90 deg) such peak was not found. Further, it was found that for Chroma and hue peripheral flicker sensitivity around "red" and "green" base-color points is lower than that of "blue". Moreover, sensitivity to Chroma flicker is the lowest when the color is varied around "green", whereas sensitivity to hue is the lowest around "red". In fact, Chroma variations around "green" are virtually undetectable in the periphery of human vision. In the second experiment it was found that peripheral flicker sensitivity is impaired when mental load is included and a scaling factor for calculating this difference in lightness flicker was obtained (2.9 for frequencies <20Hz and 1.2 at 40Hz). Finally, in the third experiment, it was discovered that flicker visibility thresholds are smaller in the central than in the peripheral vision. A scaling factor to calculate the difference between central vision and 35 degrees with no mental load was obtained.

Currently, there exists no model which defines color perception in peripheral vision. In this research, a model for central vision was used and it was shown that, even though a series of meaningful findings were obtained, a more suitable model is needed. This study can lay basis for creating such a model. More work on the subject is recommended.

Findings from this study are useful is designing LED-based lighting applications.

Contents

Introduction

We live in industrialized societies, where the technological progress is very rapid. Various technological novelties appear all the time with a very fast pace in virtually every life area. In the field of lighting systems, LEDs (Light Emitting Diodes) have become more frequently used in recent years. That is because of a series of advantages of such systems over the conventional, analogue lighting systems (like light bulbs). One of the most important advantages of LEDs is their dynamic capability. They can easily generate and change a wide range of chromaticity and brightness levels over time. This in turn allows for their use in many applications, which range from common indicators and road signs, to personalized atmosphere creation. It is therefore clear that the range of application of LEDs is very wide, making their design very important.

One of the main challenges in the design and control of the dynamic lighting systems is the perceived attractiveness of the produced temporal light changes. LEDs are controlled in a way that produces chromaticity and brightness changes in discrete steps at discrete time intervals. However, one issue appears here. When the size of these steps is too large the light change is perceived as jerky, or unsmooth. For most applications such effect is highly undesirable.

Flicker is one example of such effects, and from the perspective of perceived attractiveness, it is an especially annoying one. Flicker is defined as a repeated and quick light alternation. Different light systems can flicker for different reasons. They may be broken and thus produce flickering light, they may be wrongly controlled, or in some special cases flicker is desirable (like at the disco). LEDs flicker at specific frequencies which are measured in Hertz. Under some particular conditions, for example for very high frequencies (about 80 Hz and more) the change is not perceived as flicker any more but instead it appears to fuse and a steady, continuous source of light is visible (Truss, 1955). Previous studies demonstrated that flicker perception is influenced not only by frequency, but by numerous other factors, which include luminance (Hart Jr, 1987), chromaticity irrespective of brightness (Kelly, 1974), size of the stimuli (Hecht & Smith, 1965) and finally the retinal position of the stimuli (Tyler & Hamer, 1990).

The current study aims at defining the maximum distance between colors in LCh color space (defined as ΔE) at which alternating light produces steady, and not flickering, patterns. In order to be able to define such distance the notion of visibility threshold has been introduced (MacAdam, 1942). It is defined as the largest amplitude (the distance in change between two colors) for the particular stimuli that produce steady and not flickering light changes.

A few years ago Sekulovski at el. (2007) conducted a research in which they have shown and roughly defined the flicker visibility threshold in the central vision. However, LED based lighting systems can also be extended to the peripheral vision. Extending LEDs lighting systems into the periphery has a series of advantages with the increase of the perceived attractiveness being the most important one. It is however known that, due to the structure of human eye, the perception of motion and color changes in the periphery. For that reason one particular alternating color pattern that appears to be steady in the central vision may be perceived as flickering in the periphery and vice versa. Thus, the results from Sekulovski et al. (2007) cannot be assumed in the periphery and a new research is required.

In the current study three experiments were conducted. Their main goal was to investigate the change of the flicker visibility threshold as a function of frequency in the periphery. Moreover, this project aims at determining the effect of color chromaticity and different colored light properties (hue, Chroma and Lightness) on the flicker visibility threshold in human peripheral vision.

In Chapters 2 and 3 background information necessary to understand this project are provided. Chapter 2 describes human color vision and Chapter 3 describes human teporal vision, stressing flicker perception. Chapter 4 provides introduction of the current research. In Chapters 5 through 7 the experiments, together with their results, are described. In Chapter 5 the peripheral flicker sensitivity under mental load is presented. Chapter 6 presents comparison of peripheral flicker sensitivity with and without mental load. Chapter 7 presents comparison of flicker senstivity in central and peripheral vision. In Chapter 8 general discussion of the results is presented. Finally, Chapter 9 provides short conclusions.

Human vision

This chapter provides information on human vision, which are important to understand this project.

Color Vision

It is difficult to precisely define what color vision is. It is namely not an objective feature of the physical world, but it is not an illusion, either. Color vision is a result of neurons' interactions in our brain. There is no such a thing as a color in the external world; it is however created by neurons and projected into the external world that we see. Color is fundamentally a complex judgment experienced as sensation. Color vision has evolved in humans to facilitate detection and discrimination of objects, which is illustrated at *Figure* 2.1. It is perfectly visible that with color the floral scene presented is better understood; the boarders of the individual objects (e.g. flowers) are distinguished, whereas without colors the given scene is somewhat vague.

Figure 2.1: A scene with and without color

Light and the spectrum we can see

Sight is the sense organ of radiant energy. It evolved in relation to the surfaces and objects that absorb, reflect or refract solar radiation. Humans respond to only one small portion of the entire light spectrum. Light is the electromagnetic radiation that stimulates the eye. This stimulation depends on both energy (frequency, expressed as wavelength) and quantity of light (number of photons).The *Figure* 2.2 shows the visible spectrum on a wavelength scale, roughly as it appears in sunlight reflected from a diffraction grating (such as a compact disc), which produces an equal spacing of light wavelengths.

Spectral power distribution, light sources and illuminants

In order to accurately and completely describe the light, and consequently color, light's radiant power (energy per second) at each wavelength in the visible spectrum should be given. As a result a spectral power distribution (SPD) of light source is obtained. It contains all the basic physical data about the light and it allows for quantitative color analyses. From the

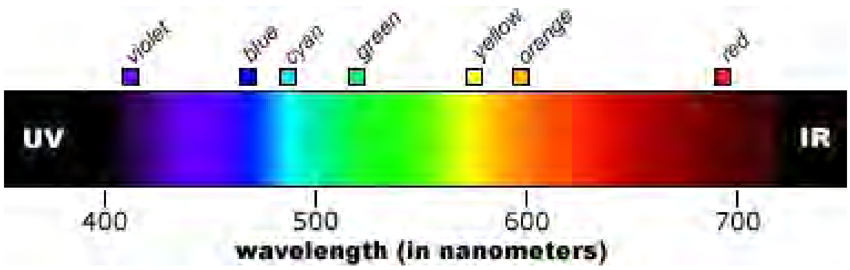

Figure 2.2: The visible electromagnetic spectrum

SPD both the luminance as well as chromaticity of color can be derived and consequently the color can be described (usually in terms of one of the CIE systems, which is described in one of the subsequent sections). The distinction between the light sources and illuminants is also of high importance. Light sources are actual physical emitters of visible energy, e.g. light bulbs or fluorescent tubes. On the other hand illuminants are standardized tables of values or plots that correspond to the spectral power distribution (SPD) typical of some specific light source. Standardized illuminants facilitate comparison of color properties and help to avoid ambiguities in the appearance of the color. CIE has standardized, among others, representation of typical incandescent, daylight of the 65K (K stands for kelvin; it is a SI unit increment of temperature) temperature and fluorescent light sources and they are named illuminants A, D65 and F2 respectively. D65 is especially interesting and very useful in color research because it is perceived as a balanced "white" illumination. Across a wide range illumination levels - rain or shine, we perceive daylight as white light (provided it is not near the horizon) *Figure* 2.3 shows the spectral power distribution as a function of wavelength for daylight phases across the spectrum (Fairchild, 2005).

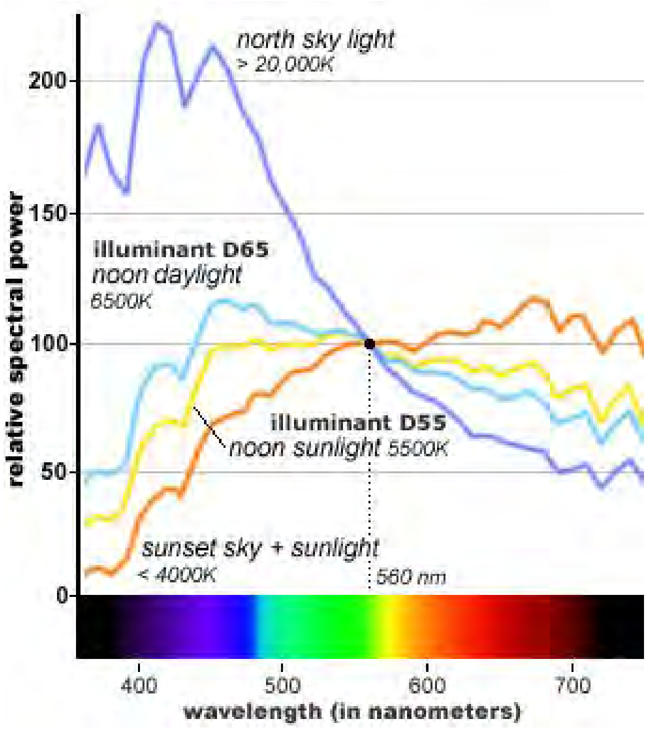

Figure 2.3: Spectral variations in natural light

The eye is adapted to function across illumination levels from 0.001 lux (starry night) to more than 100,000 lux (noon daylight), which makes humans perfectly functional day or night (lux is the SI unit of illuminance). Moonlight has the same spectral power distribution as daylight, though much reduced in intensity, so the D65 illuminant stands for the daylight and nighttime extremes of natural light experience. However, our color experience of light and objects changes dramatically within that illumination range, as the eye changes from trichromatic "photopic vision" to monochromatic "scotopic vision", which concepts are discussed in the next section.

Human Eye

It has to be understood that properties of human vision are central to understanding the perception of flicker. *Figure* 2.4 shows the structure of human eye, description of which falls outside the scope of this report. The emphasis is however placed on the parts which have to be understood, namely human retina with its photoreceptors.

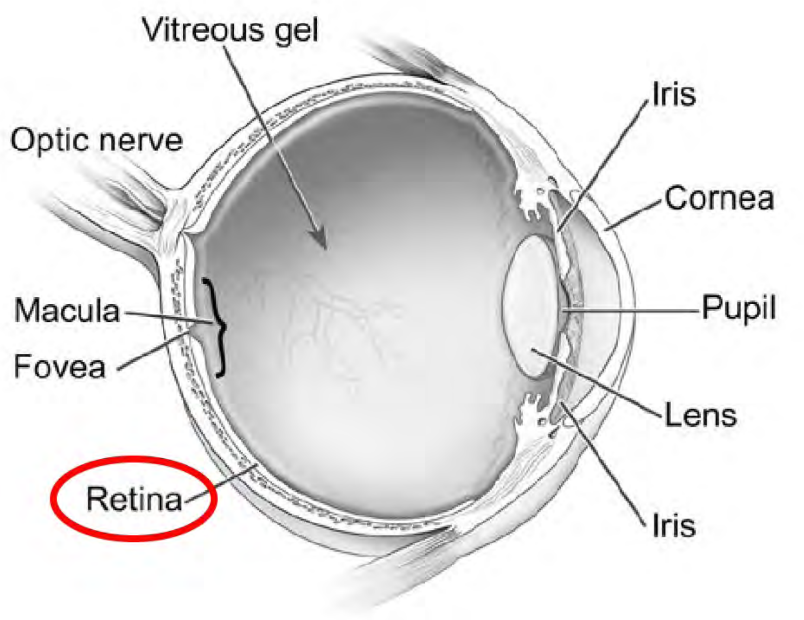

Figure 2.4: Structure of human eye

Human Retina and Photoreceptors

The human retina is a light-sensitive tissue at the back of the eye that covers about 65% of its interior surface. It is less than half a millimeter thick. In the center of the retina there is a small spot called the fovea, where the eye's sharpest and most vivid colored vision occurs. Retina contains a dense mosaic of photoreceptors, namely rods and cones, which are cells, specialized to detect light. They convert incident light energy into signals that are carried to the brain by the optic nerve. In the middle of the retina, in the fovea, there are exclusively cones. The density of rods increases when moving away from fovea, while the density of cones decreases. There are about 5 million of cone cells of three types and about 100 million of rod cells. The density of rods and cones is shown in *Figure* 2.5.

The duplicity theory developed by J. von Kries (1929) states that cones are receptors used for daylight vision while rods are effective only at extremely low light levels. Night vision, or vision at low ambient light levels, is frequently referred to as "scotopic vision" while daylight, the one at high ambient light levels, vision is called "photopic vision". Between those two there is also a range of "mesopic vision" where both rods and cones are active. Rods have a much

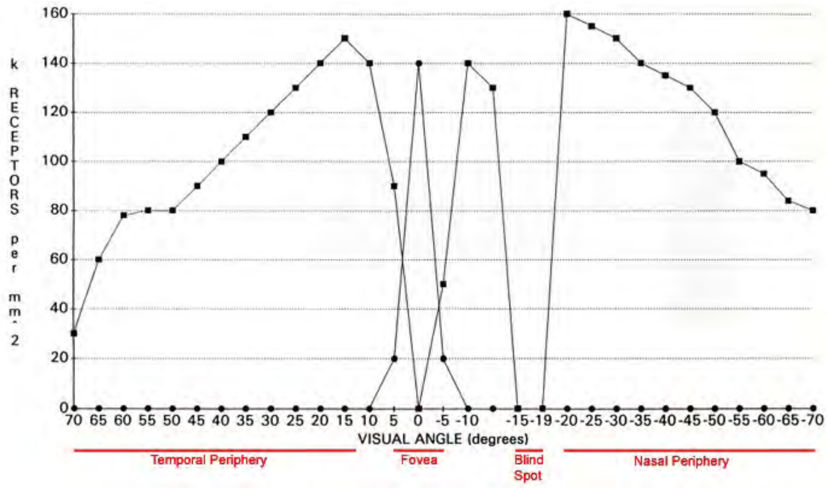

Figure 2.5: Rods and Cones distribution in human retina

higher sensitivity than the cones. However, the sense of color is essentially lost in the scotopic vision regime. A luminance of white light above about 3 cd/m^2(cd stands for candela and it is SI unit of luminous intensity; it is power emitted by a light source in a particular direction, weighted by the luminosity function), is considered as photopic, and a luminance below 0.002 cd/m^2 is scotopic, while the mesopic ranges between 0.001 to 3cd/m^2. *Figure* 2.6 shows the intensity range for humans' visual system and receptor regimes (Poynton, 2003; Coren et al., 1994; Walberg, 2005).

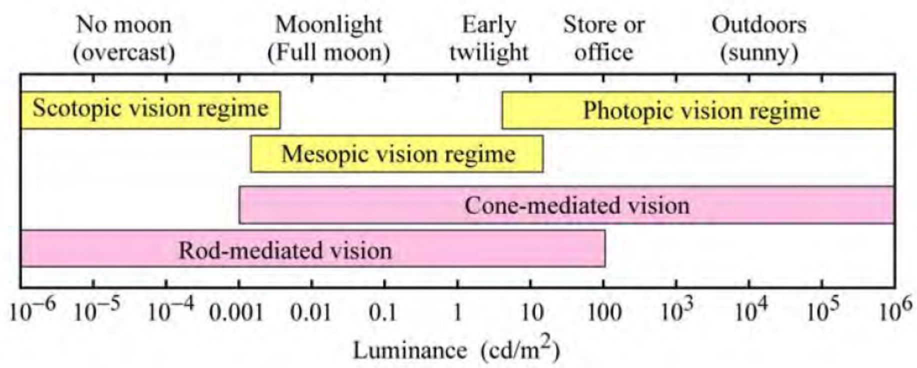

Figure 2.6: Sensitivity range for human visual system

Humans have three types of cone cells, each having different spectral sensitivity and pigment, which allows for both chromatic and achromatic vision. Cones are named after the spectral region they embrace: there are L-, M-, and S-cones, which are sensitive to long, medium and short light waves respectively. The wavelength for which the sensitivity is maximum is 560 nm for L-cones (matching greenish-yellow and red), 530 nm for M-cones (matching yellowish-green), and 425 nm for S-cones (matching violet and blue). *Figure* 2.7 shows the spectral sensitivity of rods and cones normalized to equal peak values of 1.0 on a linear, vertical scale. The inspection of this figure reveals that night vision is weaker in the red spectral range and thus stronger in the blue spectral range as compared to daytime vision.

The M- and L-cones are concentrated in the fovea. The S-cones have the highest sensitivity and are mostly found outside the fovea, leading to some distinction in the eye's blue perception. The stimuli of each cone type don't reach the brain independently of each other. Rather, they

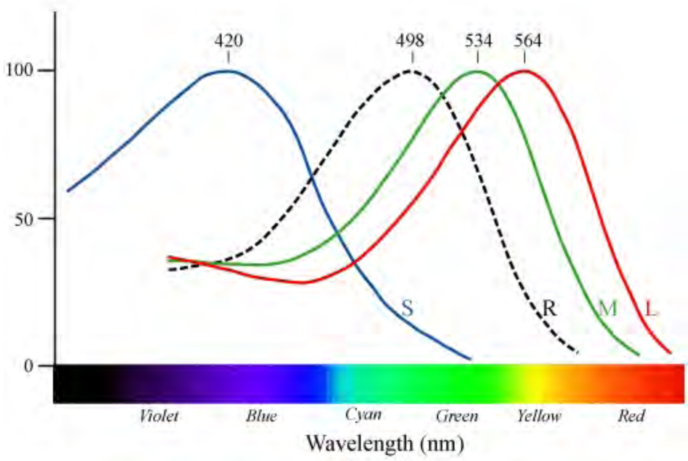

Figure 2.7: Normalized spectral sensitivity of retinal rod and cone cells

are combined already in the retina forming so called opponent channels: two chromatic ones: L - M, S - (L + M), and one achromatic one: L + M. The first two channels are commonly known as "yellow-blue" and "red-green", whereas the latter one is luminance channel, which is shown of *Figure* 2.8. It has only relatively recently emerged that these channels' mechanisms are mediated by anatomically, physiologically, and morphologically distinct retinocortical pathways, the detailed description of which falls outside of the scope of this report. It is however important to remember that color information undergo a series of transformation between retina and cortex (Murray et al., 2006; Poynton, 2003; Coren et al., 1994; Walberg, 2005).

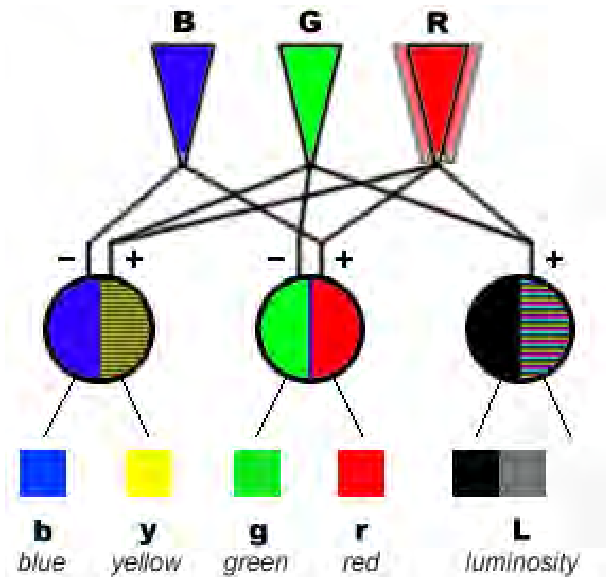

Figure 2.8: Opponent processing of cone outputs

There is only one type of rod cells, all with the same pigment. Therefore, what is commonly called night vision cannot provide for color differentiation and cannot discriminate fine details. An object is in fact seen better when we focus a little to the side of it because the central fovea is rod-free. The sensitivity in the dark is higher a little to the side of the fovea, where the density of the rods is the highest. A weak light, being just visible in the periphery of the visual field, will disappear when we try to fixate it directly on the fovea. It is also easier to detect motion with night vision, as rods are better motion sensors. Loss of rods leads to night blindness (Walberg, 2005). In the dark-adapted eye (rod vision), sensitivity has a maximum at 505nm, while in the light-adapted eye (cone vision), sensitivity peaks at 555nm. The curves representing the spectral luminous efficiacy for human vision on log vertical scale are shown on *Figure* 2.9.

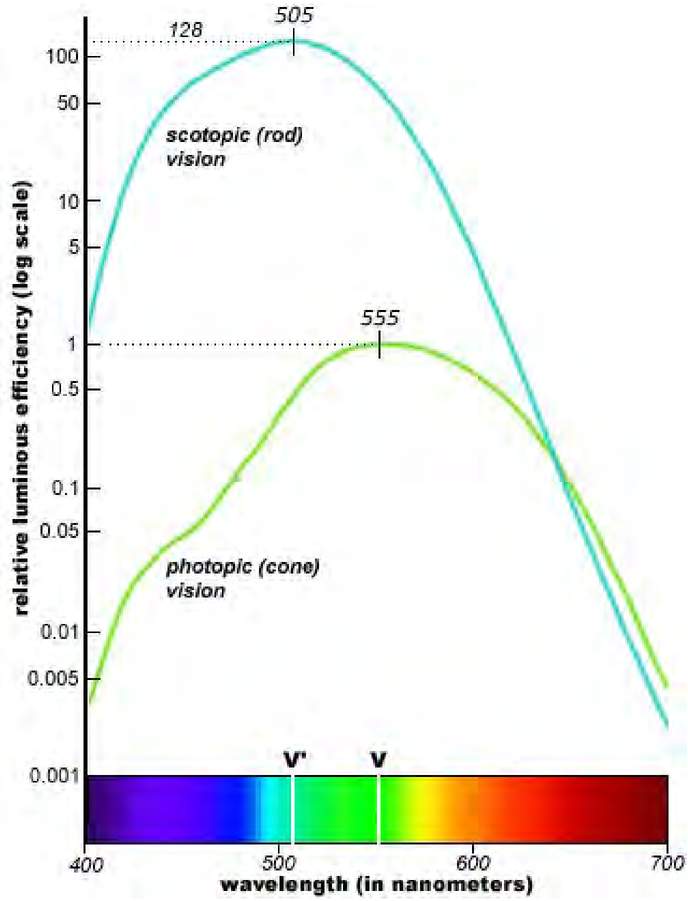

Figure 2.9: Photopic and scotopic sensitivity functions

What is interesting, in the dark-adapted eye, the absolute sensitivity of the rods for wavelengths longer than 650nm is slightly lower for the L-cones. Therefore, under red light conditions, humans have sharper cone vision without losing the high rod sensitivity. Also, it accounts for the growing apparent brightness of green leaves at twilight. Rods respond much slower than the cones to light stimulation. In rods the effect of absorption of light quanta is summed within about 100 ms. This enables rods to detect faint light, but it has a side effect that the rod signals cannot be modulated in time faster than about 10 - 15 Hz. The cones respond much faster, with a summation time of between 10 and 20 ms at higher time levels. The rise time is short and they also return much faster to the resting potential as soon as the stimulation is over. This allows for better temporal resolution, and measurements of flicker sensitivity have shown that cones can follow up to 80 - 90 Hz (Lee et al., 1990; Poynton, 2003; Coren et al., 1994; Walberg, 2005).

Although, the relative excitation of cones cannot be directly connected to the perceived color the three numerical components (variables) are necessary and sufficient to describe a color. Hence, color vision is inherently trichromatic. The lack of one of the cone types results in dichromacy, which in turn leads to color confusion (most commonly people fail to distinguish between red and green). To arrange for three components to mimic color vision, suitable spectral sensitivity functions must be used, which topic will be discussed in the chapter on CIE (Walberg, 2005; Poynton, 2003).

Putting it all together

From the discussion so far it can be easily deducted that the perceived color of the surface depends on various factors. Firstly, spectral content of the ambient illuminant and selective reflectivity of objects are important. Light is a mixture of many wavelengths. The precise mixture of the wavelengths is determined by the light source and its emissive properties. Once this mixture of wavelengths reflects off the surface of an object the mixture is changed. It is important to emphasize that some wavelengths are absorbed more than others by particular surfaces. The resulting mixture of wavelength carries the information about the color of an object. Thus, spectral data is a complete and unambiguous description of color information. Secondly, perceived color also depends on humans' individual properties. *Figure* 2.10 illustrates the casual process leading to color vision.

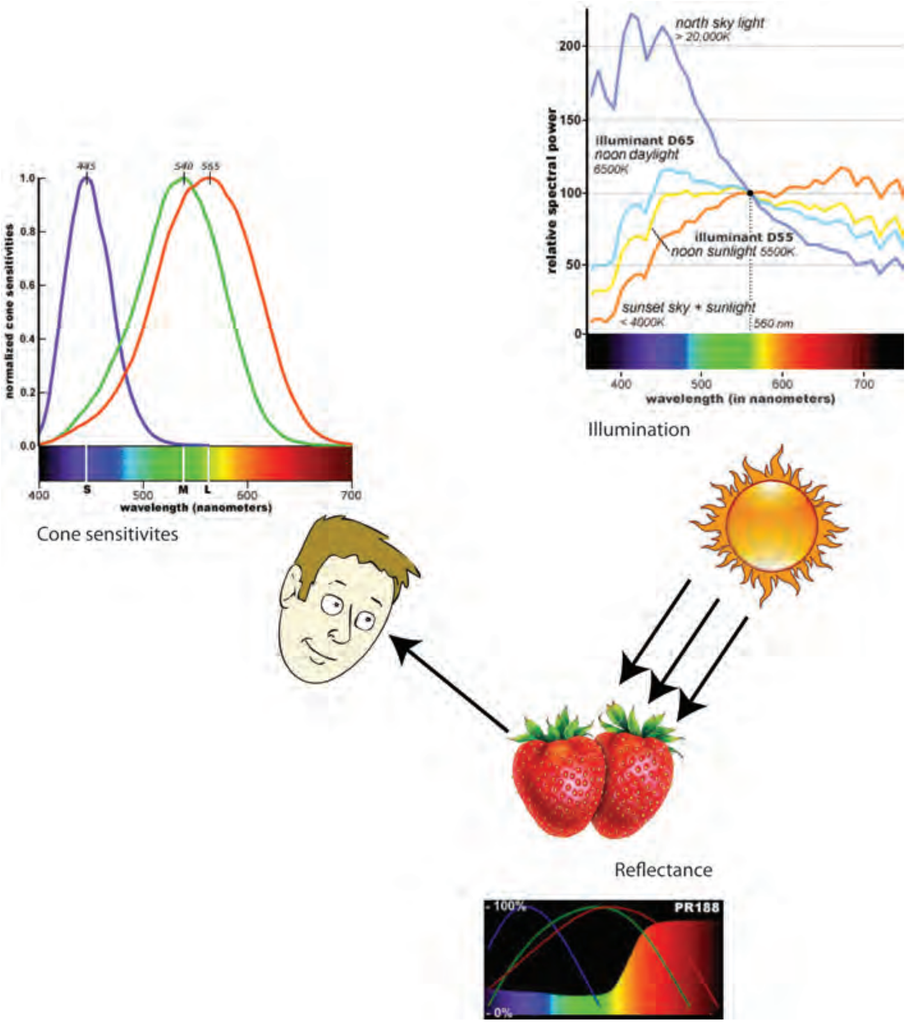

Figure 2.10: Color vision process

Adaptation

The two vision systems, scotopic, mediated by rods and photopic, mediated by cones are designed to deal with different light levels. Even within only one system, human eye has to adjust its sensitivity every time the light level varies. The changing of retinal sensitivity in response to overall light level is called *adaptation*. The four types of adaptation, important in this project are: light, dark, chromatic anf flicker adaptation.

Light Adaptation

Light adaptation can be best explained with an example. Let's assume, that a girl is getting into the sunny midday from a dark room (like theater). At the beginning she becomes "blinded" by the light, and is not really able to see anything. After a few seconds however she is perfectly able to see all the objects around. What happened is that her mechanisms of vision were at their most sensitive in the dark room (low ambient light vision). When getting into the light they got overloaded due to their high sensitivity. After a few minutes they light adapted, meaning that their sensitivity decreased which allowed for normal vision (Fairchild, 2005).

Dark Adaptation

Dark adaptation is similar to light adaptation, just it functions in the opposite direction. If the same girl walks from the midday sun into the dark room, the room appears too dark and consequently she cannot see anything. However, as the retina adapt to the lower light level, hence it increase its sensitivity, more and more things can be seen. It takes about half an hour to become completely dark adapted (Fairchild, 2005).

Chromatic Adaptation

Chromatic adaptation is the largely independent sensitivity regulation of the mechanisms of color vision. An illustrative example of chromatic adaptation are *afterimages*. Normally, eye is preventing from afterimages by rapidly moving small amounts all the time. However, if the colored image is large enough so that these small movements are not enough to change the color under one area of the retina, those cones will eventually adapt and stop responding. When the eyes are later diverted to a blank, preferably white space, the adapted photoreceptors send out a weak signal and those colors remain muted. Then again, the surrounding cones that were not being excited by that color are still "fresh", and send out a strong signal. The signal is exactly the same as if looking at the opposite color, which is how the brain interprets it. Chromatic adaptation is thus, among other reasons, the ability of human visual system to discount the color of a light source and to approximately preserve the appearance of the object.

Flicker Adaptation

Flicker adaptation is a phenomenon defined by a difference in sensitivity. It was found that human sensitivity to temporal fluctuations of light intensity is lower after adaptation to a flickering light than it wis after adaptation to a steady light of the same time-average retinal illuminance (Pantle, 1971). More detailed description of flicker adaptation is in the following section.

Color Attributes

Color occurs in the mind but it is a response to light in the world. For this reason separate color descriptions are necessary for the external, physical stimulus and the subjective color perception. This section deals with the subjective side of color, which is essentially described by three colormaking attributes: brightness/lightness, hue and chroma/colorfulness/saturation. These allows for a sufficient and reliable description of isolated color areas under simple viewing conditions.

Brightness and Lightness

When defining the changes in light intensity coming from some scene or isolated light source brightness is considered. However, the sensation of brightness also depends on the actual state of adaptation. The same dimmed room appears to have different levels of brightness when entering it from the sunny midday and when waking up during the night inside it. On the other hand the perception of individual surfaces that reflect the light is called *lightness*. The sensation of lightness does not depend neither on the state of adaptation nor the overall illuminance. The handkerchief will appear white and a black cat will always appear black no matter if one is in the bright sunlight or in the dimmed room. Therefore, the sensation of lightness corresponds to the relative intensity coming from each surface. The black cat appears black because it reflects less light than other objects near it, while the handkerchief reflects more light relative to other objects. Humans respond to the ratio of a light from an object compared to that from its surroundings, and that ratio remains constant even though the overall illumination or state of adaptation changes. This kind of response is referred to as *lightness constancy*. All objects always remain their level of lightness regardless of the other factors (Fairchild, 2005).

In other words, brightness refers to the total amount of light emitted by a light or reflected from a surface, while lightness refers to the amount of light reflected by a surface in comparison to a white surface under the same illumination. Thus, lightness can be expressed with the equation 2.1.

$$Lightness = \frac{Brighhtness}{Brightness(White)} \tag{2.1}$$

The variation in lightness, while other colormaking attributes, chroma and hue are kept constant, is showed on *Figure* 2.11.

Figure 2.11: Differences in Lightness

Hue

Hue is the most recognized color attribute; it's the quality that is recognized with the main color or color name, such as yellow or blue. It is what distinguishes one spectral color from the other. For example all reds differ from yellows, regardless of any other possible similarities. Following CIE "*hue is the attribute of a visual sensation according to which an area appears to be similar to one of the perceived colors, red, yellow, green and blue, or a combination of two of them.*" Human perception of hue is determine by the dominant wavelength of an SPD. If it shifts, the hue of the associated color will shift accordingly. Colors can be divided in terms of hue into *achromatic colors* and *chromatic colors*. The first ones are color devoid of hue, whereas the latter ones are colors possessing hue. It is important to realize that even though color without hue can be described, there is no perception that corresponds to a meaningful hue of zero units. Thus the color appearance models never try to describe hue with more than an interval scale (Fairchild, 2005). The variation in hue, while lightness and chroma are kept constant, is shown on *Figure* 2.12.

Figure 2.12: Differences in hue

Colorfulness, Chroma and Saturation

Color perception is generally thought of as being three-dimensional. Chroma/colorfulness/saturation is thus is the third color's attribute. Colorfulness is to chroma as brightness is to lightness i.e. chroma is a relative colorfulness. Colorfulness describes the intensity of the hue in a particular color stimulus. Consequently, achromatic colors exhibit zero colorfulness and chroma. As the amount of color content increases (with constant brightnhess/lightness and hue), colorfulness and chroma increase as well (Fairchild, 2005). Similarly to lightness, chroma is constant across changes in luminance level. However, it is important to realize, that chroma is likely to change if the color of the illumination is varied. Colorfulness, on the other hand, increases for a object as the luminance level increases since it is an absolute perception quantity. In other words, chroma is a colorfulness of an area judged as a proportion of the brightness of a similarly illuminated area that appears white or highly transmitting, which is shown in equation 2.2.

$$Chroma = \frac{Colorfulness}{Brightness(White)} \tag{2.2}$$

The change in chroma, while lightness and hue are kept constant is shown on *Figure* 2.13.

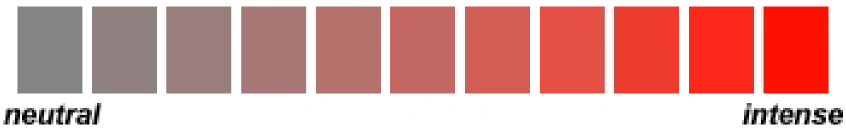

Figure 2.13: Differences in chroma

Artists and others more often use the term saturation to refer to chroma, although strictly speaking these represent different ways to define color intensity. Saturation is namely the chromatic intensity of a color judged in relation to its own brightness. *Figure* 2.14 illustrates the difference between chroma and saturation (which is S on the graph). Chroma changes horizontally in equal perceptual steps. The colored rectangles in each row of the diagram have the same lightness, whereas rectangles in each column are of the same chroma.

Human peripheral vision

Peripheral vision, as its name implies, is a part of vision that occurs in the periphery, outside the very center of eyes' fixation. There is a vast set of non-central points in the field of view that is included in the notion of peripheral vision. In general, ”far peripheral” vision exists at the edges of the field of view (90 degrees), ”mid-peripheral” vision exists in the middle of the field of view, and ”near-peripheral”, sometimes referred to as ”paracentral” or ”parafoveal” vision, exists adjacent to eyes' fixation center. Some of the aspects of the peripheral vision have already been discussed under the section: Human retina and photoreceptors. It is important to keep in mind what is the structure of human retina and the density of rods and cones together with their properties. Generally, peripheral vision is good at detecting motion (a feature of rod cells), and is relatively strong at night or in the dark, when the lack of color cues and lighting makes cone cells far less useful.

Peripheral Color Vision

The perception of color depends upon which region of the retina receives the image of the perceived object. It has been shown that peripheral color vision is qualitatively different than foveal vision. In general, color vision is best in the center of fixation but its quality declines when moving away into the periphery. This fact goes hand in hand with the inferior spatial

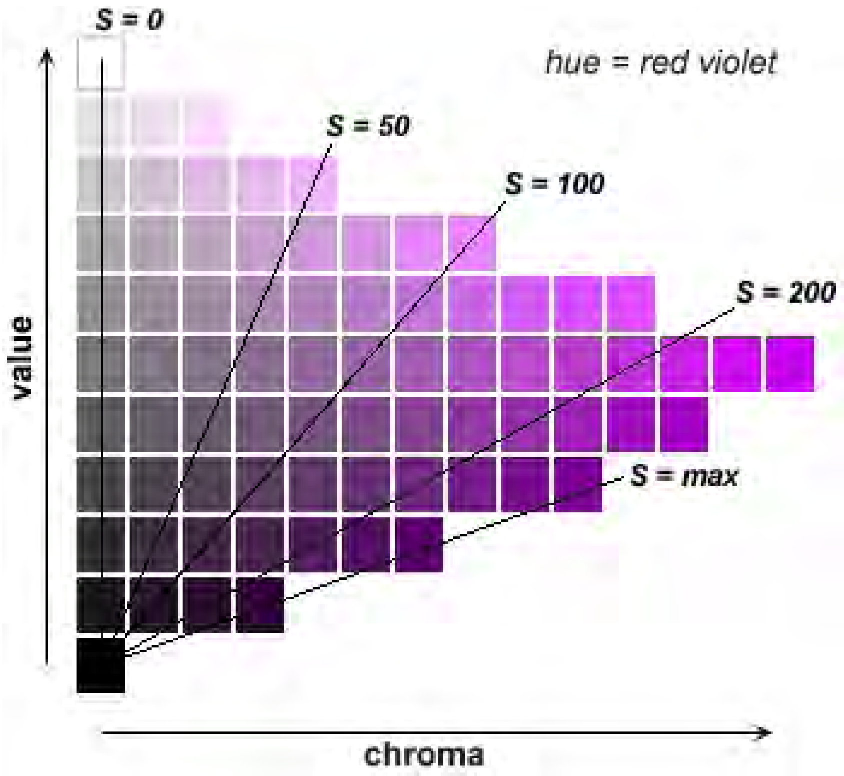

Figure 2.14: Variations in lightness, chroma and saturation (S) for a violet hue

abilities of eccentric vision. Peripheral color vision is of high importance, especially as an aid to speed up the search process (Kayser and Boynton, 1996).

First of all, Abramov and Gordon (1977) showed that the photopic luminosity function, as defined by heterochromatic flicker photometry, is not the same in the periphery of the retina as it is in the fovea. While the foveal functions are normal, the peripheral ones show a large enhancement in sensitivity to short wavelengths relative to long wavelengths (Abramov and Gordon, 1977).

Moreland (1972), in his review on peripheral color vision, confirmed the finding that the ability to discriminate color deteriorate as a stimulus is moving further into the peripheral retina. Color perception becomes nearly dichromatic at eccentricities between 25 and 45 deg and monochromatic at even greater eccentricities. Moreover, Moreland (1972) showed that peripheral color discrimination is quite good for large stimuli. When the size of the stimuli field was increased as eccentricity was increased, ability to discriminate colors was almost constant (Moreland, 1972). This finding was confirmed by Kayser and Boynton (1996) who demonstrated that while small peripheral targets appear desaturated and of uncertain color, large targets, especially if they are very bright, can mediate good color perception similar to that of central vision (Kayser and Boynton, 1996). Nagy and Wolf also (1993) showed that foveal and peripheral wavelength discrimination functions were similar in shape when large stimulus field was used in the periphery. Therefore, they suggested that color coding mechanisms are similar in the fovea and in the peripheral vision except for a change in spatial scale. Presumably, larger stimuli are needed in the periphery because color coding neurons are more sparsely distributed in the peripheral retina than in the fovea (Nagy and Wolf, 1993; Moreland, 1972). One of the most recent studies by Murray et al. (2006) also confirmed that indeed peripheral saturation can be neutralized if the test stimulus is increased in size, however this compensation does not apply to hue shifts, which is independent of stimulus size (Murray et al., 2006).

Based on the above findings it is clear that discrimination thresholds for a stimulus of a fixed size increase with increasing eccentricity. This increase is found to be an exponential function of eccentricity and is similar for all of the long-wavelengths *Figure* 2.15. Naggy and Wolf (1993) interpreted it to mean that the fovea is specialized for processing chromatic differences.

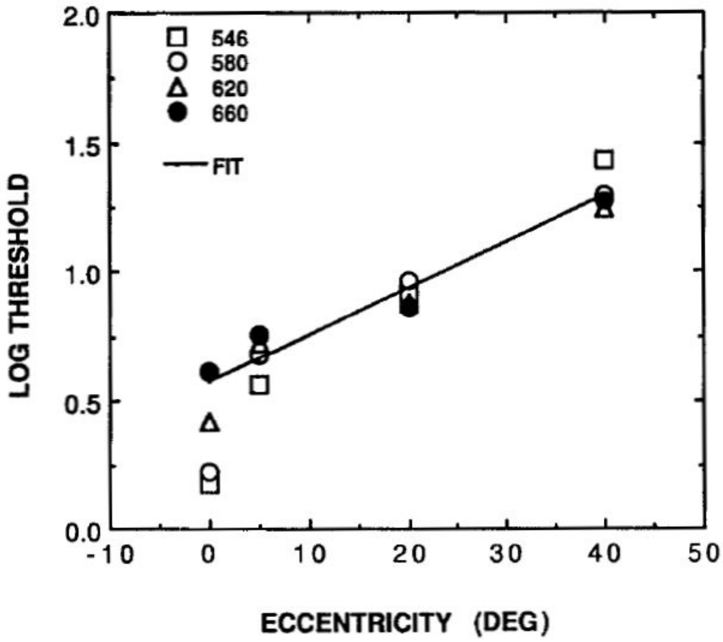

Figure 2.15: Log threshold plotted as a function of eccentricity. The straight line was fit with a least-squared-error criterion to the peripheral data points

Nagy and Wolf (1993) also converted the color differences at threshold to distances in the CIELuv color spaces. This color space was found to represent color differences for peripheral stimuli reasonably accurately, even though it was developed for central vision (Nagy and Wolf, 1993). In the section on human retina and photoreceptors, the two color-opponent channels have been briefly discussed. It was demonstrated, through color naming and asymmetric matching experiments, that the sensitivity to red-green color variations (which corresponds to L - M channel) deteriorated more rapidly toward the periphery than sensitivity to luminance or blue-yellow colors (which corresponds to S - (L + M) channel). At 20 deg the reduction in red-green sensitivity is claimed to be 85% greater than that for achromatic or blue-yellow sensitivity. This decrease in color performance is likely a result of the spatial organization of the retina and not just the loss in sensitivity. The number of spectrally opponent ganglion cells decrease with eccentricity, their receptive fields (RFs) get larger, and non-opponent cells becomes cone opponent if the stimulus size is increased. Also, the fovea has a large representation in the cortex, while the peripheral retina projects to a relatively smaller area in primary visual cortex.In psychophysical studies by Mullen et al.(2005) it was found that after 20 - 25 deg eccentricity to the L - M cone opponency becomes behaviorally absent and the luminance system becomes more sensitive than any of the chromatic systems. However, physiological experiments in macaque monkeys have shown that midget ganglion cells exist in the intermediate zone of the peripheral retina (20 - 50 deg) and that they are strongly cone opponent. Hansen et al. (2009) explored this contradiction between physiological and psychophysical research, using stimuli at eccentricities of up to 50 deg. They revealed that chromatic detection gets worse with increasing eccentricity but is still possible even at large eccentricities. Their results showed that chromatic detection at these eccentricities is indeed mediated by cone-opponent mechanisms. They measured chromatic detection and discrimination in the near periphery and found that chromatic discrimination, in particular along the L - M axis, is possible even at high eccentricities up to 50 deg for stimuli of at least 8 deg size. It was confirmed in three control experiments (identification, detection in cone contrast space, and chromatic discrimination) that chromatic mechanisms indeed operate at these eccentricities (Hansen et al., 2009; Moreland, 1972; Murray et al., 2006; Mullen et al., 2005).

Color zones

Only in a recent few years, research on the color zones in peripheral vision emerged. It is important in order to clarify the color perception mechanism as well as for improving various applications such as color appearance of traffic signs and signals. The color zone map is a contour map covering the entire visual field, which shows how perceived strength of redness, yellowness, greenness, or blueness (called the "unique hue components") changes with eccentricity from the center of the visual field (Sakurai et al., 2003). In their research Sakurai and Ayama firstly demonstrated that hue shifts toward unique yellow or blue and there is a decrease of saturation observed for all of the stimuli (Ayama and Sakurai, 2003). In their next study they showed that the hue of the red and green stimuli shifts toward a unique yellow, while that of yellow and blue does not change with increasing eccentricity. It is considered to be caused by a steeper decline in the activity of the red-green opponent mechanism than in that of the yellow-blue mechanism. Moreover, the saturation of all the stimuli decreases with increasing eccentricity, which is explained by a decline in the activity of the chromatically opponent mechanisms relative to that of the achromatic mechanism (Sakurai et al., 2003). The next research on the subject by Hamada and Yujiri revealed that the color zone of the retina extended further into the periphery with increasing luminance. In addition, it has been clarified that the reduction in opponent colors yellow-blue sensitivity is smaller than that of red-green (Hamada and Yujiri, 2004).

Colorimetry

This section lays the basis for the color spaces comprehension, which is crucial to understand this project.

Tristimulus

In the part on the photoreceptors, it has been pointed out that normal human vision is mediated by three types of cones with different spectral sensitivities. They are usually defined with S, M, and L, which stands for short, medium and long wave sensitivity. Therefore, it is said that the color vision is trichromatic and consequently three quantities or values are necessary and sufficient to describe a color. A three-dimensional color space is therefore implicit in a system with three receptor types. Just about every form of color measurement is tristimulus or trichromatic. Trichromacy is thus the foundation of colorimetry (Tkalcic and Tasic, 2003).

Metamerism

The importance of trichromacy is that since the responses are simplified to only three values, different spectral outputs could easily result in the perception of the same color. This simplification is named "metamerism", and it means that we are able to match color among objects with different spectral properties. This type of color matching is termed "metameric", which is different than the spectral match that would refer to the spectral outputs of two stimuli being identical.

RGB, CMY(K) and color spaces development

RGB stands for red, green and blue, and it is a description of a color as a combination of these three primaries. CMY(K), similarly to RGB, describes the color in terms of three primaries, namely cyan, magenta and yellow. There are however a few issues with RGB and CMY(K). First of all ”red”, ”green” or ”blue” are just names that were given to represent a particular part of the spectrum. The exact set of wavelength is system-dependent and the only requirement is that the spectral sensitivity curves need to overlap themselves and cover the entire visible spectrum. In other words, there exist many possible primary sets and as a result many potential tristimulus spaces. On the other hand, not all of the tristimuli systems describe color in terms of primaries. One of the advantages of tristimuls color description is that it can be plotted in three dimensions. It means that every color can be represented by a unique point in space defined by the three coordinates, which all is commonly known as a *color space*. Over the years different color spaces have been developed and description of all of them falls outside the scope of this report. I will describe the ones which are important for comprehension of this project, emphasizing CIE Lab color space, which serves as a model basis in the current research (Bunting, 1988; Overheim and Wagner, 1982).

The CIE

The International Commission on Illumination (from French: The Commission Internationalle de LÉclairage, but the author of this report don’t understand any French) is considered to be the color ”guru”. Its aim is to develop a system which would facilitate specification and communication of colors of different products. In short, CIE defined *Standard Observer, Standard Illuminants, CIE XYZ primary system, CIE xyY color space, CIE chromaticity diagram* and later also *CIE LAB* and *CIE LUV* color spaces. The key concepts of most of these definitions are going to be further explained and described (Bunting, 1988; Overheim and Wagner, 1982).

XYZ - CIE tristimulus values

CIE managed to define all colors in terms of three values: X, Y and Z, which system is based on human visual system. It is relatively rarely used, but it serves as a foundation for all the other CIE systems. The XYZ primaries are so called ”imaginary” ones. They can be algebraically derived from the color matching data representing any system of real primaries but in such a way that the color matches they express never require negative numbers. The ”green” primary (Y) is arbitrary given a matching curve that is identical to the visual sensitivity curve of the human eye. It means that this curve represents how sensitive the human eye is to light of different wavelengths. Multiplying the green curve times the spectrum to be analyzed automatically gives the apparent brightness or lightness of the spectrum.

In short, the X primary represents the amount of ”red” needed to match the spectrum, whereas Y is the amount of ”green” primary needed to match the spectrum and the total brightness of the light. Finally Z stands for the amount of ”blue” primary needed to match the spectrum (Bunting, 1988; Overheim and Wagner, 1982). *Figure* 2.16 shows the color matching functions for the 10° standard observer (as defined by CIE) and the imaginary XYZ primaries.

xyY - the CIE chromaticity diagram

It is difficult to visualize what the color looks like just by giving the tristimulus values. Thus, derived from XYZ are the following color coordinates:

$$x = \frac{X}{(X+Y+Z)} \tag{2.3}$$

$$y = \frac{Y}{(X+Y+Z)} \tag{2.4}$$

$$z = \frac{Z}{(X+Y+Z)} \tag{2.5}$$

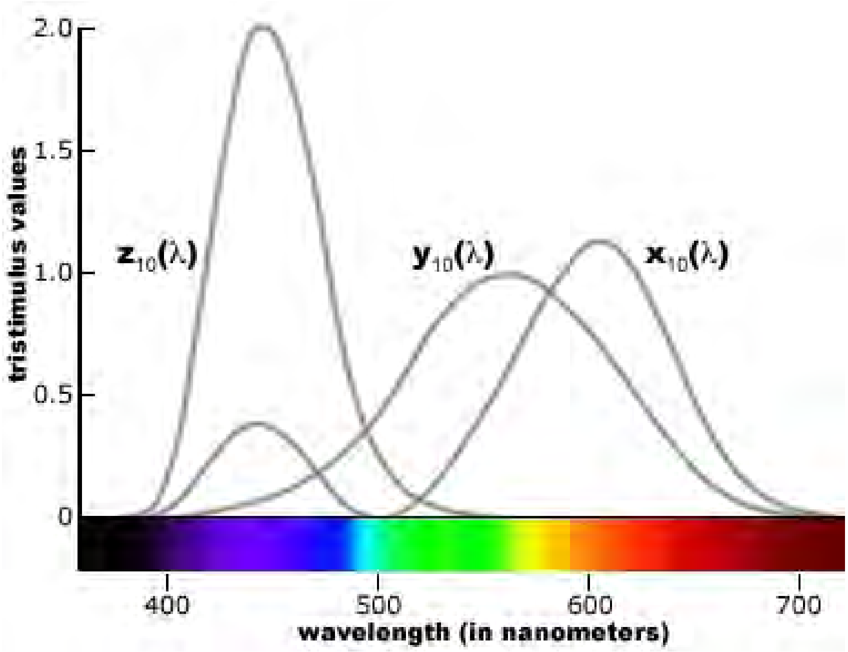

Figure 2.16: 1964 XYZ color matching functions

Obviously, x+y+z = 1, so given any two of these values, one can easily calculate the third one. In fact, the chromaticity coordinates specify only x and y (hue and saturation) of the color but not the brightness. The latter one is defined by the value of Y (the "green" tristimulus value). Consequently, the complete color description is given by: x, y and Y. The x and y values of colors has been plotted in a graph, commonly known as a CIE chromaticity diagram, shown on *Figure* 2.17 A

The center of this chromaticity diagram is neutral. As one moves away from the center the colors become more saturated. At the very edges of the diagram they represent pure spectral colors. The hue changes as one moves around the edges. For any device, e.g. monitor or printer, one can plot on this diagram a gamut, which are the colors that can be reproduced with the use of particular system's primaries. A gamut comparison across the systems is one of the most frequent uses of the chromaticity diagram. The main purpose of the chromaticity diagram, is to determine whether two colors match or not. However, as it was pointed out by MacAdams in 1942 we are not really able to tell the degree of color mismatch, because the color space is not perceptually uniform. MacAdams showed that equally large color differences are reproduced in the chromaticity diagram as different lengths, depending on the target chromaticity and on the direction from the target. This means that, for example, the same amount of difference in the yellow and purple region of the color space would not translate to equal amounts of perceptible color difference. The chromaticity diagram together with MacAdams ellipses are presented on *Figure* 2.17 B

In the attempts to solve the above problem and develop perceptually uniform color spaces CIE came up with CIE Lab and Luv.

CIE LAB and LUV

In order to solve the non-uniformity of the tristimulus value Y (which stands for luminance), CIE described a "uniform lightness scale", L*, derived from Y. L* defines lightness from black to white in perceptually equal steps, ranging from 0 (black) up to 300 (white). With the use of L*, u' and v', the CIE developed a color space universally referred to as L*u*v*, CIELUV or simply Luv. This color space is much more perceptually uniform, and it is widely used,

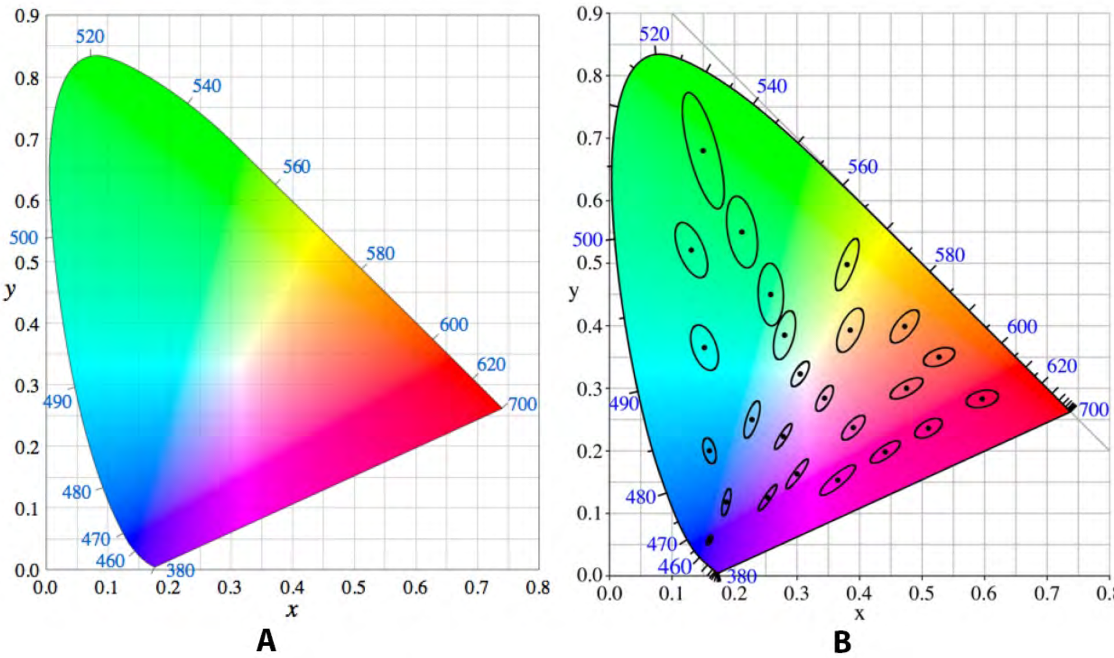

Figure 2.17: A: The CIE xy chromaticity diagram with color added to illustrate the geography of the visual plate B: MacAdams ellipses, which are ten times their actual size

especially in TV monitors, computer monitors and controlled lighting sources. One limitation of CIELUV lies in its lack of perceptual uniformity with relation to luminance, because it was found that as the lightness of a color differs, the chromaticity differences are not constant.

In a second approach to overcome the non-uniformity problem the CIE defined a* and b* derived from X, Y and Z. The a* value quite suitably expresses a uniform redness-greenness scale of a color. A* value ranges from -300 (green) to + 300 (red). As can be expected the b* value represents a uniform yellowness-blueness scale and it also ranges from -300 (blue) to + 300 (yellow). As a result the new color space is obtained, which is commonly referred to as L*a*b*, or CIELAB or simply Lab. Each color in CIE LAB is thus specified in terms of its lightness and chromaticity by three points in each axis. In order to arrive at the CIELAB color space the calculations below need to take place (equations: 2.6, 2.7 and 2.8), using the XYZ tristimulus values for the object and the white point of the illuminant (X_n, Y_n, Z_n).

$$L^* = 116(Y/Y_n)^{1/3} - 16 \tag{2.6}$$

$$a^* = 500[(X/X_n)^{1/3} - (Y/Y_n)^{1/3}] \tag{2.7}$$

$$b^* = 200[(Y/Y_n)^{1/3} - (Z - Z_n)^{1/3}] \tag{2.8}$$

LCh

In the current research yet another color space is used, namely LCh, which is essentially identical with CIELAB, but the chromatic values are expressed in terms of chroma and hue instead. It is then clear that LCh stands for Lightness, Chroma and Hue, which attributes have already been described in previous section and which can be calculated from CIELAB using the formulas: 2.9, 2.10.

$$C^* = (a^2 + b^2)^{1/2} \tag{2.9}$$

$$h^\circ = arctan(b^*/a^*) \tag{2.10}$$

LCH has a form of a sphere and it consists of three axes (see *Figure* 2.18). The vertical L* axes represents Lightness and it ranges from 0 (black) to 100 (white). The horizontal C* axes represents Chroma and it ranges from 0 at the very center of the circle (grey, where Lightness equals to 50) to 100 or more at the edges. Chroma is to be understood as the intensity, or vividness, of a hue that increases as the specified color moves further away from the grey axis. The higher the value of chroma, the more pure, vivid, or saturated the color is. Hue is the main attribute of the color, and it allows to know whether it is green, red, orange, and so on. It is specified in a radius from 0 to 360 degrees, starting from the positive side of the a* axis and moving counterclockwise. The fact that color perception is three-dimensional means that each color specification coordinate is affected by the other two. This means a color's hue would shift to a certain degree when its lightness or chroma changes. It must be emphasized that LCh does NOT have a circular shape. *Figure* 2.18 presents LCh color space in its simplified form (A) and the regular one(B) (Tkalcic and Tasic, 2003).

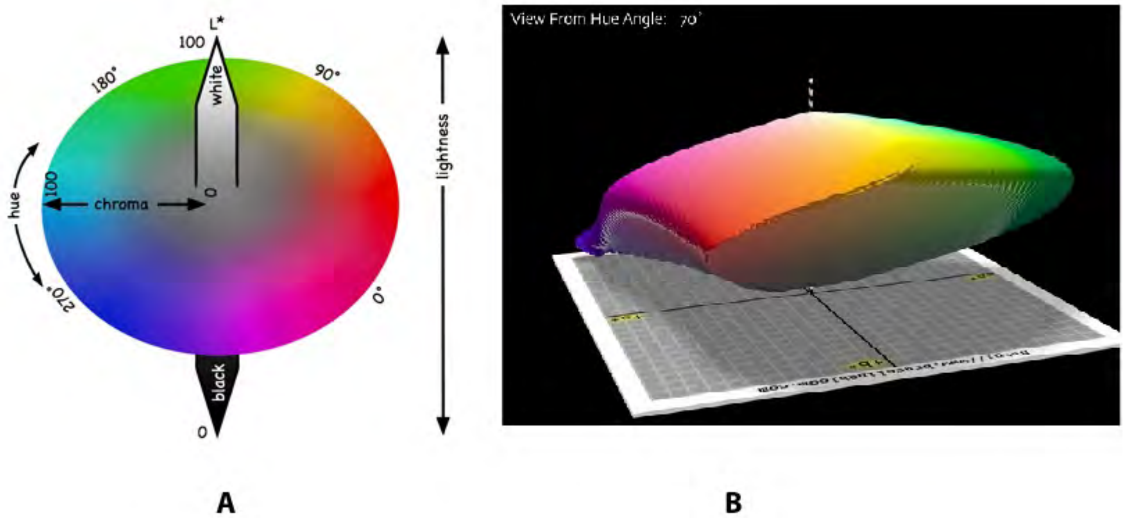

Figure 2.18: A: Simplified LCh color space B: LCh color space

The beauty of perceptually uniform color spaces is that they facilitate accurate calculations of the magnitude of perceptual color difference between a standard color and a sample. Human color vision differs from individual to individual, and it is affected by a number of external parameters like the lightning conditions or the surrounding color. What is more, the human eye has an excellent ability to determine whether there is a color difference, but its ability to quantify the magnitude of that difference is poor. Having instruments that are able to measure two colors and unambiguously determine the magnitude of difference has significant benefits. The color difference between two measured colors can be expressed as their difference, and this number is known as ΔE. The equation used to compute it is called the color difference equation. For LCh the color difference equation is as follows:

$$\Delta E_{ab} = \sqrt{(\Delta L^*)^2 + (\Delta C^*_{ab})^2 + (\Delta H^*_{ab})^2} \tag{2.11}$$

where

$$\Delta H^*_{ab} = 2\sqrt{C_a C_b sin(\Delta h_{ab}/2)} \tag{2.12}$$

The main purpose of the CIE color spaces was to determine as accurately as possible the magnitude of perceptual color difference between a standard color and a sample.

Temporal Vision: Human sensitivity to Flicker

Flicker perception

Flicker is type of a visual event which involves a change in time. In order to understand the concept of flicker, imagine having a firefly trapped in your hand. The firefly's tail blinks on and off and consequently your closed hand emits a flickering glow. Lights that blink, flicker or wink are virtually everywhere in industrialized societies. Different kinds of these lights have different applications. The ones atop a police car or ambulance aim at capturing attention; others (the flashing light at a railroad crossing) try to warn you from a possible danger. In order for flashing lights to be effective they must flicker at a proper rate, which would be easily perceptible.

The most extensively studied field of flicker relates to the Critical Flicker Frequency (CFF), which is defined as the highest rate of the flicker which can be perceived as such. In case when this highest frequency is exceeded the separate flashes of light blend together and as a result a continuous light is being perceived. Under the optimal conditions human's CFF reaches 80 Hz. However, there is virtually endless number of options and there are similarly several numbers of complications caused within the visual system, a number of which will be described in this section. The temporal frequencies which are best visible have been studied and roughly defined. In order to determine these frequencies, light's intensity is varied over time, usually in a sinusoidal way. This allows for assessing the minimum visible fluctuation of light for a range of frequencies. *Figure* 3.1 presents the dependence of the flicker frequency and contrast sensitivity for different luminance levels.

The horizontal axis represents flicker rate and the vertical axis represents contrast sensitivity. What can be read from this graph is that human flicker sensitivity differs across luminances as well as frequencies. Threshold sensitivity increases with luminance up to about 300 cd/m2, where flicker sensitivity peaks at around 10 - 20 Hz. CFF at the *Figure* 3.1 it is a point at which the given frequencies curve crosses the x-axis (Walberg, 2005). CFF is however depended on many other variables. The intensity and size of the target light have been the most studied and best recognized. Swanson et al. (1987) confirmed that both mean luminance and filed size affected sensitivity. Moreover, they showed that data for 0.9 to 90 Td converge at high frequencies when plotted in terms of amplitude sensitivity. Sensitivity to high temporal frequencies increases faster with mean luminance than sensitivity to low temporal frequencies. Finally, they demonstrated that the magnitude of field size effects is dependent on mean luminance (Swanson et al., 1987).

It is important to emphasize that different rates of flicker are processed by separate visual mechanisms, as it was shown in a study about flicker sensitivity in glaucoma patients. Typically, patients had diminished flicker sensitivity in the surroundings of 30 Hz, while their sensitivity to other frequencies remained normal (Tyler, 1981). The following sections cover in more details different subjects related to flicker.

Luminance flicker

There were a few studies investigating the effect of luminance (lightness or brightness) on flicker perception. It was found that with the increase of the retinal illuminance causes the sensitivity to flicker increases as well (Kelly, 1974; de Lange, 1985). *Figure* 3.1 illustrates this dependency.

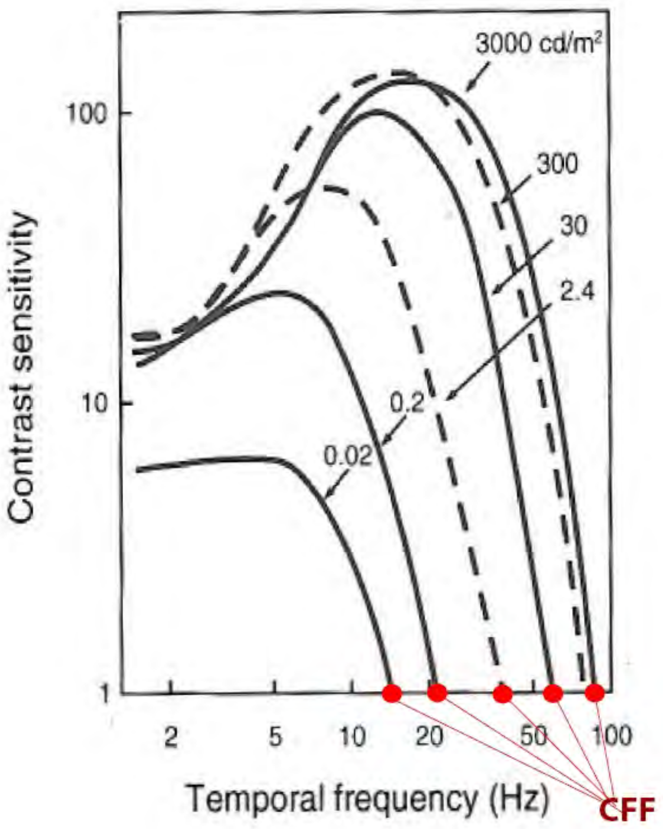

Figure 3.1: Flicker frequencies for different luminance levels (Walberg, 2005)

Chromatic flicker

As it has been described in the previous chapter, humans process colors through two separate channels, namely S - (L + M), which is known as a yellow-blue channel and L - M, which is also called red-green one. It has been recognized that chromatic flicker is also processed through these two channels and a series of studies was conducted to elaborate on it. Metha et al. investigated the temporal mechanisms underlying flicker detection and identification specifically for red-green and achromatic flicker over a range of temporal frequencies. They found out that temporal frequency identification is better for the achromatic than for red-green stimuli. Moreover, the level of chromatic identification performance they recognized was still sufficient to reject the previously accepted concept that the red-green mechanism embodies a single temporal filter (Metha and Mullen, 1996). Another study stressed the blue-sensitive mechanism of color vision. It was argued that the maximum flicker fusion frequency is about three times lower for the blue-sensitive mechanism of color vision than that for the red- or green-sensitive ones. Flicker, is thus one property of temporal visual system for which the blue sensitive mechanism differs from the others (G.S. Brindley and Rushton, 1966). Van der Horst, in his study, used sine, square, and triangular waveforms and demonstrated that the contrast-transmission system for chromatic flicker operates practically in a linear manner up to Chromatic Criticla Fusion Frequency (CCFF) of 7Hz. The chromatic fusion point was defined as when lights of two different colors alternate at a rate that the chromatic flicker disappears and hues fuse. When the brightness of the two colors is not equated to each other a brightness (lightness) flicker will be seen above this chromatic fusion frequency (van der Horst, 1969).

Rod-cones interactions

Overall, there are two types of flicker: scotopic and photopic ones, depending on the light level. It has been demonstrated that the scotopic flicker sensitivity is dependent on frequency. The results from Nygaard and Frumkes (1985) suggest that low and high frequency rod-dependent flicker sensitivities have several unique properties most probably representing the functioning of distinct channels with distinct time constants of response (Nygaard and Frumkes, 1985). There have been also a number of research in which not only the two types of flicker has been considered separately, but the interactions between rods and cones have been investigated. It has been shown that the dark-adapted rod system can reduce the flicker sensitivity of the cone system at temporal frequencies above 20Hz. Light-adapting or bleaching the rod system increases cone flicker sensitivity (Alexander and Fishman, 1984). Furthermore, Coletta and Adams demonstrated that the enhancement of cone-detected flicker sensitivity as rods become light adapted is most apparent for long wavelength stimuli. The rod-cone interaction disappears abruptly at a constant level of steady state cone adaptation and, at higher light levels, cone flicker sensitivity is enhanced by stimulation of surrounding cones (Coletta and Adams, 1984).

FM scaling

It is possible to scale stimuli so that the stimulus area and luminance are constant across the visual field. So called F-scaling and M-scaling has been used in a series of studies to make CFF independent of visual field location. More detailed research revealed that CFF to photopic green targets and to yellow-red cone targets irrespective of luminance became independent of visual filed location when MF-scaled. On the other hand, CFF to mesopic and scotopic green targets did not become independent of visual field location despite MF-scaling (Raninen and Rovamo, 1986). Yet another study showed that red MF-scaled targets at different levels of luminance increased with increased eccentricity (Raninen et al., 1991). These differences between colors are important and should be kept in mind, as they might provide explanation for our results. Then again, the current study is of more practical type; we do not scale our stimuli in any of the ways, and therefore the detailed explanation of these scaling techniques falls beyond the scope of this project. For those, who would like to get into the details, please refer to studies by Rovamo and Raninen (Rovamo and Raninen, 1988, 1984).

Peripheral flicker

CFF also changes with the different eccentricities, or to put it simple the location in the visual filed. It may happen that the rate of flicker of large stimulus (e.g. television set) is too fast to be perceived when you directly look at it, but it becomes highly visible when you move it to your peripheral vision. Temporal-frequency characteristics were measured as a function of retinal location, with test test-field size scaled to provide equivalent sensitivity at each eccentricity. It has been demonstrated that peak sensitivity to uniform modulation remains approximately constant when filed size is increased according to the cortical magnification factor. These results revealed that the decrease in CFF with eccentricity is determined by ganglion cell density at all retinal locations (Tyler, 1985). Further studies by Tyler however showed that stimulation of equal number of cones at each retinal location did not result in equal CFF values (Tyler, 1987). More detailed studies by Tyler explain CFF changes across different eccentricities in terms of lateral inhibitory effects; for further details please refer to (Tyler and Hamer, 1990; Tyler, 1987).

Mental workload and flicker perception

In the current research the human sensitivity to flicker will be studied under the mental workload. It is therefore important to control for the mental load included. The ability to remain focused on goal-relevant stimuli in the presence of potentially interfering distractors is of high importance. Recent studies revealed that processing of distractors depends crucially on the level and type of load involved in the processing of goal relevant information. High perceptual load can entirely eliminate distractor processing and therefore it is essential to consider the level and type of load involved in the task performed. This concept is known as load theory (Lavie, 2005). Carmel et al. (2007) generalized the findings of load theory into the temporal domain. Through their study they wanted to find out if the availability of processing resources could affect the temporal resolution of conscious flicker perception. Their aim was to realize if conscious perception of flicker near the CFF threshold depends on the allocation of limited capacity attention. This was achieved by varying the level of perceptual load in a visual search task comprising letters arranged in circle around fixation and by assessing the effect this had on the perception of flicker at around the CFF threshold. Their results clearly demonstrated that increasing of the perceptual load indeed impaired flicker perception. A fundamental aspect of visual perception, the parsing of temporal patterns, has therefore limited capacity and consequently depends on the availability of attention. More generally, the temporal resolution of conscious perception is determined by the attention availability (Carmel et al., 2007; Lavie, 2005).

Adaptation to flicker

When fixating on a flickering disk presented peripherally, one realize that the disk rapidly appear to lose contrast and stop flickering. This effect is called adaptation. Studies by Scheting and Spillmans (1987) suggested that adaptation to flicker in the periphery is (among others) dependent on the temporal frequency of the stimuli; high frequencies adapt faster than the low once. However, Hammett and Smith found the opposite results, namely that the time required to adapt increase with temporal frequency (Hammett and Smith, 1990). More recent studies by Anstis (1995) refuted Hammett's and Smith's finding revealing that indeed the temporal decay rate increased with flicker rate. His results also demonstrated that the contrast threshold for flicker increased logarithmically over time. Moreover, the slope of the temporal decay function increased with eccentricity and with decreasing stimuli size (Anstis, 1996).

Introduction: Current reaserch as a follow-up study

The current study is a follow-up reasearch. A few years ago Sekulovski et al. (2007) as a part of their study investigated the flicker perception in the central vision. Here, their main findings concerning flicker are summarized.

"Lightness changes are more visible than changes in Chroma and Hue, when the color changes are expressed in the CIELab color space."

"The visibility threshold for changes in Lightness decreases with frequency up to about 10 Hz and increases for larger frequencies."

The visibility thresholds for changes in Chroma and Hue are similar for frequencies up to about 10 Hz and increases for larger frequencies."

"The visibility thresholds are larger for higher Lightness levels for frequencies smaller than 10 Hz. For higher frequencies the thresholds for higher lightness levels are smaller than lower Lightness levels."

"There is a significant effect of chromaticity of the base color points for changes in Chroma and Hue. The sensitivity for the different base color points differs for Chroma and Hue."

The current study focuses on peripheral, and not central vision. What is more, the mental load and its effect on flicker perception is introduced here.

All of the color spaces developed by CIE (with LCh among them) are exclusively valid in the central vision and not in the periphery. The structure of human eye, and especially retina and photoreceptors, differs significantly when moving away from the fovea. It was repeatedly indicated that the ability to discriminate color deteriorates as a stimulus is moving further into the peripheral retina (see the section on Human peripheral vision). Moreover, the photopic luminosity function, as defined by heterochromatic flicker photometry, is not the same in the periphery of the retina as it is in the fovea. Therefore, the results from Sekulovski et al. cannot be assumed in the periphery. On the other hand, the hypotheses developed in this research are, in addition to the literature review, based largely on their findings (Abramov and Gordon, 1977).

What is more, most of the previous studies investigated human flicker sensitivity in terms of Critical Fusion Frequency (CFF). As long as this concept defines the maximal frequency value at which flicker is not percieved anymore, it does not provide information about sensitivity at lower frequencies. However, from the aplication perspective it is important to recognize flicker sensitivity at frequencies defined by specific devices.

Experiment 1

Flicker perception in the periphery under mental load

Introduction

The goal of the first experiment of the current study is to find out what is human sensitivity to flicker at various eccentric visual angles and frequencies while simultaneously performing mental load task. The literature review provided in the previous section lay background for the questions which are to be answered through this experiment.

First, it is hypothesized that the larger the visual angle the less sensitive humans get to flicker; especially for chroma and hue changes. There are hardly any cones in the periphery of human retina. For that reason chroma and hue changes should virtually not be visible at large (more than 35 deg) eccentricities. On the other hand, it was found that humans are able to perceive some colors at large eccentricities (more than 50deg) because cone opponent-channels, however sparse, are still present at these angles. Consequently, it is hypothesized that flicker perception gets impaired with the increasing eccentricity, yet it does not disappear completely Hansen et al. (2009).

Three primary base color points were used in the current research: red, green and blue. ”Blue” cones can be found in human peripheral retina, whereas ”red” and ”green” cones are almost exclusively located in the fovea. This suggests that in the periphery humans are more sensitive to changes around the blue base point. On the other hand, in their research, Brindley et al. (1966) stressed the blue-sensitive mechanism of color vision. They found that the maximum flicker fusion frequency is about three times lower for the blue-sensitive mechanism of color vision than that for the red- or green-sensitive ones. Their study was conducted exclusively in the central vision, and therefore its application into the periphery is not certain. Studies by Sekulovski et al. (2007) revealed that humans are more sensitive to changes around ”blue” rather then ”red” and ”green” base points. They explored flicker sensitivity as a function of frequency. Finally, it was demonstrated that the sensitivity to red-green color variations (which corresponds to L - M channel) deteriorates more rapidly toward the periphery than sensitivity to luminance or blue-yellow colors (S - (L + M) channel) Hansen et al. (2009). Based on the discussed findings, it is hypothesized that flicker sensitivity in peripheral vision to red and green is worse than sensitivity to changes around blue base color point. Moreover, previous findings imply that the differences between red, green and blue base color points become larger when moving away into larger eccentricities G.S. Brindley and Rushton (1966); Sekulovski (2007).

It was found that in the central vision, flicker sensitivity increases with the increasing luminance Walberg (2005) Kelly (1974). Further, it was indicated that this sensitivity has a maximum value, and so it peaks at around 10 - 20Hz Walberg (2005) or at around 10Hz Sekulovski (2007). There is no research exploring luminance flicker in human peripheral vision. However, lightness flicker is known to be cone-independent (it does not require color perception). Therefore we believe that the above findings generally apply in the periphery of human vision. It is hypothesized that the sensitivity to lightness flicker increase with increasing lightness levels. Moreover, sensitivity to lightness flicker has its defined maximum value.

Sekulovski et al. (2007) found that, in central vision, humans are more sensitive to Lightness flicker than to Chroma and hue flicker. Similarly, Metha et al. (1996) demonstrated that temporal frequency identification is better for the achromatic than for red-green stimuli. Moreover, it was repeatedly demonstrated that with the increasing eccentricity perceived colors loose their saturation, which is explained with the density of rods and cones on human retina (for details see: Human Retina and Photoreceptors). These findings suggest that sensitivity to lightness flicker is higher than that of Chroma and hue also in the periphery Beurden et al. (2007)Sakurai et al. (2003); Metha and Mullen (1996); Sekulovski (2007).

Most of the previous studies on human flicker sensitivity were conduced exclusively in human central vision. These findings were considered when formulating hypotheses for the current research. However, they cannot be taken for granted and their complete generalization to the peripheral vision might be erroneous (for detailed reasons see previous sections). The current study has somewhat exploratory character because almost no research on peripheral flicker perception was conducted. Therefore the hypotheses, however accurately formulated, should be treated with proper care.

Method

Participants

Participants were 10 female and 20 male Philips Research employees, aged between 23 and 45 years, with a mean age of 29 years. In order to be able to take part in this experiment, subjects had to fulfill a series of conditions. They had to have normal or corrected to normal vision, not wear glasses, had normal colorvision (which was checked for with Ishihara Test for colorblindness), not suffer from epileptic attacks, migraines or any other disorders for which it was found that flickering light could have negative consequences, and finally they did not have family members with known history of such disorders. All of the participants fulfilled these conditions and signed informed consent form confirming that.

Stimuli

The stimulus was as an alternating color pattern (flicker) with an amplitude A, expressed in ΔE, frequency f and a base color point B. $1\Delta E$ (Total Color Difference) is a single number that represents the smallest, perceptible ”distance” between two colors in CIE LAB color space. The stimulus was varied around one of the base color points and along one of the axes in the LCh color space: Lightness (around the mean value of 60), Chroma (60) or hue (45, 150, 290). Care was taken that for large amplitudes of color change, the color was within the gamut of the light source. The flickering light of random duration (from 2 to 4 seconds) was alternated with non-flickering light of fixed duration (2 seconds). The non-flickering light had mean Lightness, Chroma and hue values. The schematic flicker stimuli is presented at *Figure* 5.1.

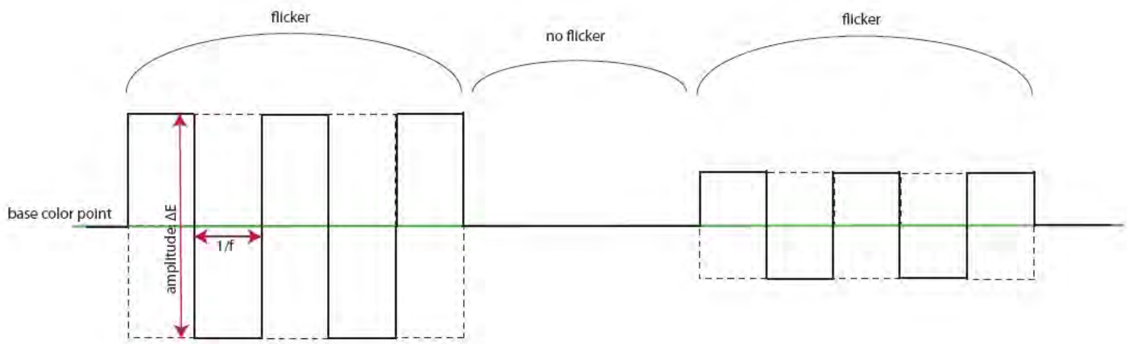

Figure 5.1: Stimuli used in experiments

Three base color points have been used in this experiment: red (which mean values in LCh color space corresponded to 60,60 and 45), green (60, 60, 150) and blue (60, 60, 290). They have been chosen because the space around them allows for large amplitudes that covers most of the LCh color space. Moreover, they are most widely used primaries elsewhere. The stimuli were presented within three blocks, randomized across the participants, and corresponding to these three primaries. There were no breaks between the blocks. *Figure* 5.2 shows the three base color points on the chromaticity diagram. The D65 white point has been assumed as a reference, as it is a standard white point for display systems and a white point of the display at which mental load task was presented (mental load task is explained in the following section).

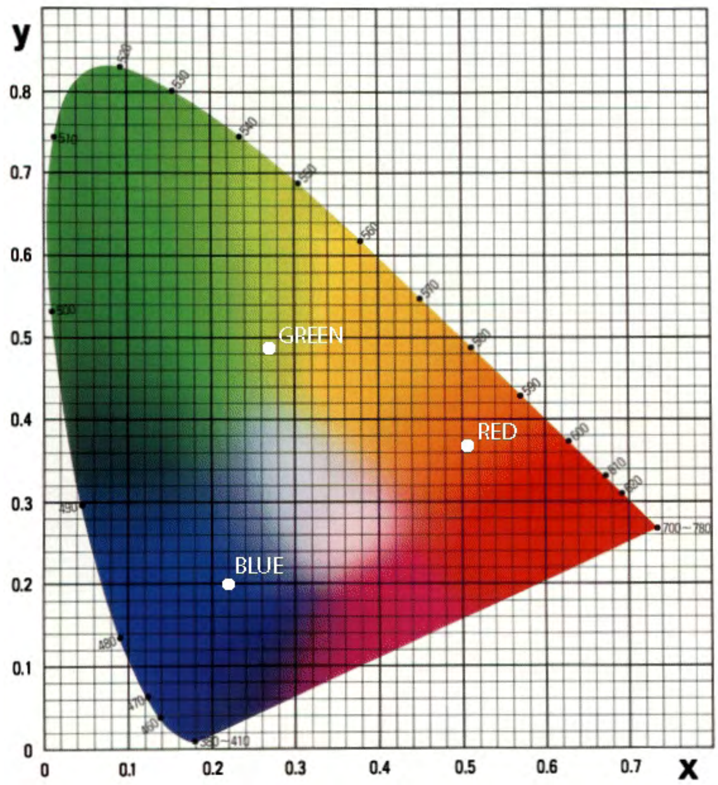

Figure 5.2: Base color points used in all three experiments

Three different eccentricities were tested in this experiment: 35, 60 and 90 deg. The 35 deg eccentricity was selected because, as according to Tyler and Hamer (1990) it corresponds to the retinal region of highest flicker sensitivity. At this eccentricity the density of both cones and rods is approximately constant for a radius of at least 10 deg around any point, and the receptor morphology is also homogeneous. The 90 deg was chosen because it is the most distant eccentricity at which human perception still functions. Finally, 60 deg was chosen as a middle value between 35 and 90 deg eccentricities. There were three sessions of this experiment, and in each of these sessions one of these three eccentricities was tested. The eccentricities were randomized across the subjects Tyler and Hamer (1990).

Mental load task

The current research investigated the peripheral flicker perception under mental workload; thus special "game" was designed and created in Adobe Flash CS3 Professional which served as a mental load task.(see *Figure* 5.3). Subjects carried out the task for the duration of the entire experiment. Four balls were displayed on the screen: three small black balls and one bigger grey ball. Participants were instructed to use a mouse to move the bigger grey ball. They had to move it in such a way that it did not hit/touch any of the the other black balls, which were in constant motion ruled by collision detections. (*Figure* 5.3 A). When the grey ball hit/touched any of the black balls, the red redHit text box appeared in the left bottom corner of the screen (*Figure* 5.3 B). When black balls hit one another or any of the boarder walls, they bounced back (a collision detection algorithm was used). This specific mental load task was used because it forced two types of eye movements: saccadic and continuous ones. Moreover, it was relatively easy to carry out and consequently it allowed for flicker perception.

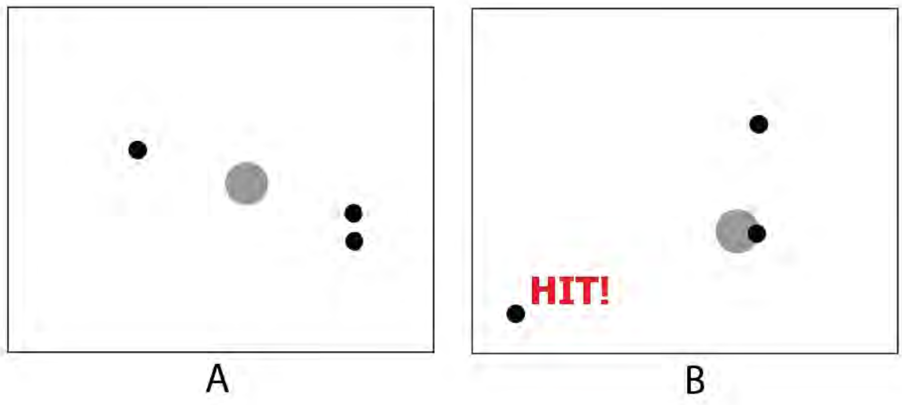

Figure 5.3: Mental load task

Design

The Experiment 1 was a within-subject design; it consisted of three separate sessions and each of the subjects completed all of them. In the study by Sekulovski et al. (2007) the adjustment (tunning) experiment was used to find the flicker visibility thresholds in human central vision. However, Nagy and Wolf (1993) conducted a study in which their subjects tried the adjustment procedure in the periphery (for color discrimination and matching experiments). They found it almost impossible to perform, and therefore they replaced adjustment with detection procedure, which was relatively simple to complete Nagy and Wolf (1993). Similarly, in the current research, the detection is used. It is a procedure during which the flickering light alternates with non-flickering light. Subjects were presented with such light in the periphery and they had to specify, by pressing the space bar on the keyboard, when they saw it flickering. Most of the time the light flickered around the visibility threshold.

In majority of studies on peripheral vision participants conducted tests monocularly, with one eye covered. It was also the initial idea in this experiment. However, it has been demonstrated by Moulden et al. (1984) that flicker threshold elevation shows interocular transfer. This indicates that at least some of the mechanisms involved in flicker perception are binocular, rather than purely monocular Moulden et al. (1984). Moreover, this project aims at a very practical application, and consequently participants undertook the experiment using both of their eyes.

The perception of flicker was measured by varying a set of variables. The design was 3x3x3x5x5: Eccentricity (35, 60 and 90deg) x Base Color Point (Red, Green and Blue) x Color Attribute (Lightness, Chroma and hue) x Frequency (5,10,20,40,60) x Amplitude (see Table 5.1 for details). Amplitude values were chosen after a series of pilot tests. Most of them were close to the visibility threshold, but it was also important that amplitudes, for which all of the subjects as well as none of the subjects could detect flicker, were included. The complete set of the conditions used for this experiment is shown in Table 5.1.

Apparatus and Materials used

A special lamp has been built for the purpose of this research. It consisted of a three RGB LEDs at the top and three RGB LEDs at the bottom of a diffuser. The lamp was moved to different

Base Color	Lightness	Chroma	hue	Frequencies (Hz)	Amplitudes(ΔE)
Red	60	60	45	5,10,20,40,60	L: 1,2,4,6,10,60 C: 10,20,40,60 h: 20,40,60,80
Green	60	60	150	5,10,20,40,60	L: 1,2,4,6,10,60 C: 10,20,40,60 h: 20,40,60,80
Blue	60	60	290	5,10,20,40,60	L: 1,2,4,6,10,60 C: 10,20,40,60 h: 20,40,60,80

Table 5.1: Stimuli for the eccentricities: 35, 60 and 90deg

peripheral positions for different experimental sessions. It was therefore more convenient that subjects looked at this lamp directly rather than at its reflection. Such kind of light source has however sharp edges, which in turn produce luminance contrast. It is known that luminance contrast can elevate flicker thresholds at low rates. This is thought to arise from the contrast created at the edge of the flickering field, which saturates edge sensitive flicker mechanism Watson (1986). To overcome the issue of sharp edges, and so to smooth them out, another diffuser was mounted about 20 cm in front of the lamp. Its detailed profile, measured from where subjects were sitting, is shown on *Figure* 5.4. The lamp was 23 cm wide and a distance from a subject to the lamp was 2.5 meters; therefore the light covered 5.3 deg of subjects visual angle.

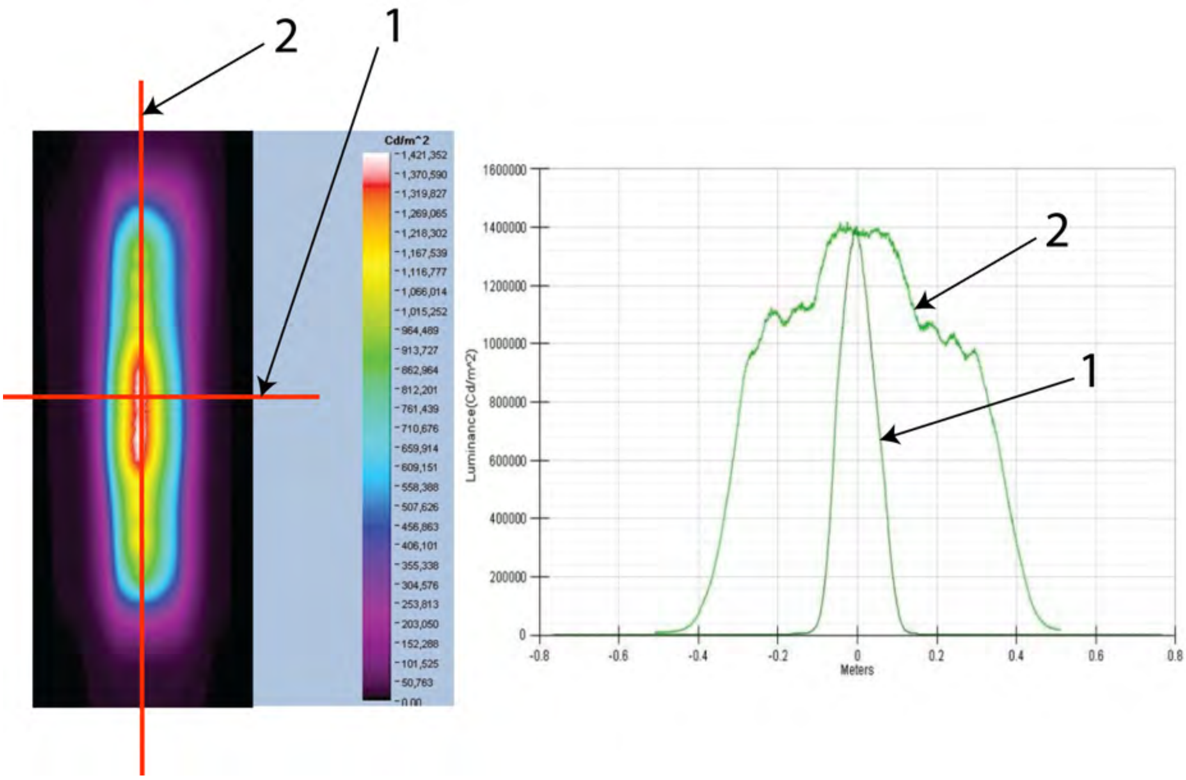

Figure 5.4: Profile of the lamp used

The stimuli were defined in LCh color space. This was subsequently translated into XYZ and then into RGB, so that the signal could be sent to the lamp. D65 white point was used as the standard white reference point of displays. All the experiments took place in the Philips Research lab, which schematic outline is shown on *Figure* 5.5

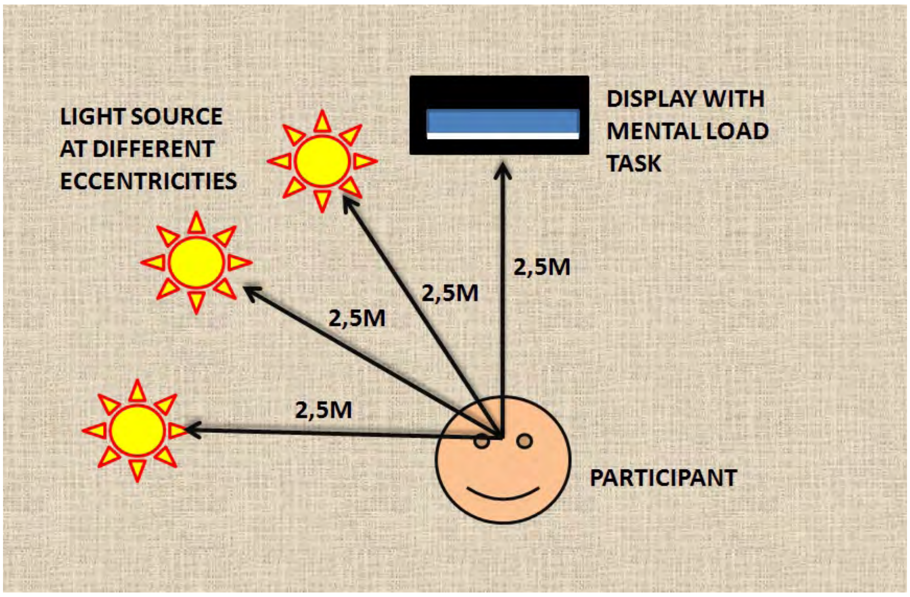

Figure 5.5: Schematic outline of the experimental room

A participant was sitting on the chair in front of the table with his chin resting on the chin standard. On the table there was a mouse for controlling the mental load task and a keyboard for detecting flicker. Both devices were connected to the computer, which in turn controlled the lamp and the display with a mental load task (19 inch). Both the lamp and the display were placed 2.5 meters away from the participant.

Procedure

At the beginning of each of the experiments a participant was welcomed, asked to sit down and read through and sign an informed consent form. His color vision was checked with the Ishara test for colorblindness. Further, he was given oral instruction of how to proceed with the experiment. He was told that its purpose was to investigate the influence of flicker on human performance, which ensured that he focused on the display in front of him. Moreover, to guarantee a fixed distance from his eyes to the display and the lamp his chin was placed on the chin rest. After a short demonstration of how different types of flickering light look like, the subject could practice the mental load task for a while, to get familiar with it. One session of the experiment took about 30 minutes. The experimenter was present in the room together with the subject for the entire duration of the experiment. After completing all three session a participant a short debriefing session was conducted.

Data Analysis

The current experiment followed a detection procedure. Therefore, the collected data did not directly yield the visibility thresholds. Instead for each unique stimulus either 0 (flicker was not detected) or 1 (flicker was detected) values were obtained. In order to get visibility thresholds a psychometric curve was fitted into each set of stimuli. The set of stimuli is defined as all the different amplitudes for each unique eccentricity, base color point, type of flicker (Lightness, Chroma or hue) and frequency. The psychometric curve ranges from 0 to 1 on x-axis. The visibility threshold is a point for which subjects over 50% of the time detected the flicker and therefore it is the 0.5 point on psychometric curve. *Figure* 5.6 shows two examples out of 45 psychometric curves obtained in this study.

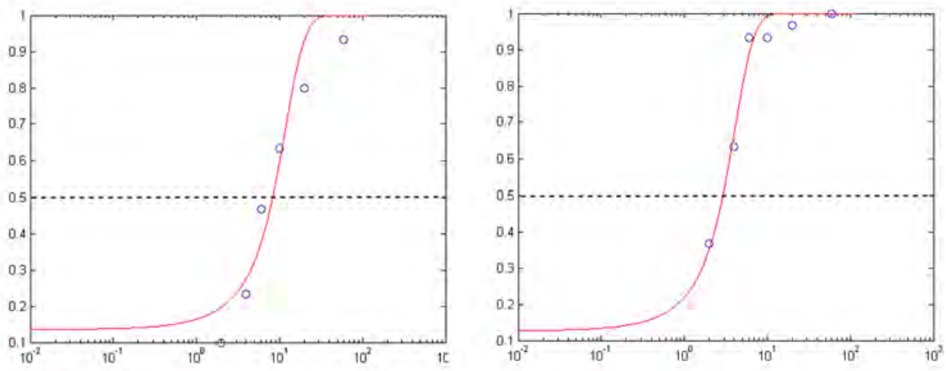

Figure 5.6: Two examples of psychometric curves

The issue with this approach was that, even though all of the thresholds were known, no confidence intervals were given. Consequently no proper statistical analysis could have been done. For that reason all of the obtained psychometric curves have been resampled 1000 times, using the bootstrapping technique. The visibility thresholds were found for each of the curves and so confidence intervals were acquired. SPSS 16.0 was used as a statistical package for data analysis. ANOVA tests were performed to check for the significance of the effects. The homogeneity of variance assumption was checked for and found not to be violated, therefore the post-hoc Tukey tests were done to check if the medians found are significantly different from one another. The graphs were produced and the error bars on each graph represent 95% confidence interval for medians. Medians were used instead of means because the later ones are more prone to errors if the sample size is as big as in this case.

Results

Overall main and interaction effects

ANOVA was run on the complete set of data, with the threshold median as dependent variable, and eccentricity (35, 60 and 90 deg), base color point (red, green and blue), type of flicker (Lightness, Chroma or hue) and frequency (5, 10, 20 and 40 Hz) as independent variables (so called fixed factors in SPSS). The results show that the main effect of the visual angle (eccentricity) significantly affected flicker perception in the periphery, $F\ (2,40) = 46{,}151$, $p<0.001$, $r = 0.775$. Pairwise comparisons revealed that 90 deg is significantly different than 35 and 60 deg, whereas the two latter ones do not differ from each other. The main effect of the base color point also significantly affected the flicker perception in the periphery, $F\ (2,40) = 116{,}813$, $p<0.001$, $r = 0.891$. Tuckey HSD revealed that blue is significantly different (lower than) than red and green base color points ($p<0.01$); whereas there is no significant difference between red and green. The main effect of the frequency also significantly affected the flicker perception, $F\ (3,40) = 118{,}199$, $p<0.001$, $r = 0.892$. Post-hoc test indicated that 20 Hz frequency significantly differs from all of the other frequencies ($p<0.01$). Moreover, 40Hz significantly differs from 5 and 10 Hz ($p<0.05$). There is no significant difference between 5 and 10 Hz as according to Tukey HSD post-hoc test. The main effect of the direction of change significantly affected flicker perception in the periphery, $F\ (2,40) = 456{,}459$, $p<0.001$, $r = 0.967$. Tukey post-hoc revealed that Lightness flicker significantly differs from Chroma and hue flicker ($p<0.01$). However, there is no significant difference between Chroma and hue. All the 2-way interaction effects have been checked for. They are summarized in Table 5.2. It reveals that the interaction between base point and frequency as well as between frequency and direction of change have relatively big size effect. It means that the higher the frequency the more effect has base color point and type of flicker on flicker perception. The remaining two interaction effects, even though they are significant, are small.

Interaction	Statistics
eccentricity x base color point	non-significant
eccentricity x flicker type	$F(4,40) = 12{,}490$, $p<0.001$, $r = 0.526$
eccentricity x frequency	$F(6,40) = 9{,}336$, $p<0.001$, $r = 0.466$
base color point x frequency	$F(4,40) = 145{,}335$, $p<0.001$, $r = 0.91$
frequency x flicker type	$F(5,40) = 42{,}453$, $p<0.001$, $r = 0.761$

Table 5.2: Overall 2-way interaction effects

The presented results showed the general effects of all the variables on flicker perception. Analyzing each type of the flickering light separately can give more insight and details about human temporal sensitivity. Thus, Lightness, Chroma and hue flicker are independently analyzed in the following sections.

Lightness flicker

The results from lightness flicker are illustrated on *Figures* 5.7 and 5.8. First, *Figure* 5.7 shows the lightness flicker visibility thresholds for different base-color points as a function of frequency for all eccentricities separately. The shape of the curves for different base points are essentially the same (they are u-shaped) for all of the eccentricities. Therefore, lightness flicker perception is independent of the base color point. There is some variation but it is so small that it can be neglected. Further, this figure reveals that the values for curves representing 35 and 60 degrees do not differ from each other at 5 and 20Hz. The highest sensitivity (which corresponds to the lowest visibility threshold) is at 10Hz for 35 and 60 degrees. Surprisingly, the visibility threshold for low frequencies (5Hz and 10 Hz) decreases with increasing eccentricity, and it reaches it maximum value of about 1.3 at 90 degrees. On the other hand, at high frequencies (20Hz and more) lightness flicker sensitivity decreases with increasing eccentricity.

Figures 5.8 illustrates the same results; but because it was found that lightness flicker is base point independent, the curves were averaged across the base color points and grouped for different eccentricities. The curve representing 35 deg is the shallowest one whereas the curve representing 90deg is the steepest one. It means that with the increasing frequency flicker sensitivity gets largely impaired at large eccentricities. Finally, it can be read from these figures that when moving away into the periphery the frequency has larger effect on flicker perception.

ANOVA was run to check for significance of Lightness flicker effects. It was found that the main effect of eccentricity has a significant effect on the flicker perception in the periphery, $F(2,11) = 450{,}473$, $p<0.01$, $r=0.968$. The Tukey post-hoc test confirmed that 90deg is significantly different from both 35 and 60deg; on the other hand 35deg does not differ from 60deg. The main effect of base-color point was found not to be significant, which confirms that lightness flicker is base-color point independent. Furthermore, the main effect of frequency has a significant effect on flicker perception, $F(3,11) = 815{,}355$, $p<0.01$, $r=0.982$. Tukey tests showed that 20Hz and 40Hz are different from all the other frequencies and each other whereas 5Hz was found not to be different from 10Hz. In addition, the 2-way interaction effect were tested for. It was found that both ”eccentricity x base color point” as well as ”base color point x frequency” are not significant interaction effects. On the other hand, ”eccentricity x frequency” has a significant effect on flicker perception, $F(6,11) = 397{,}899$, $p<0.01$, $r=0.964$.

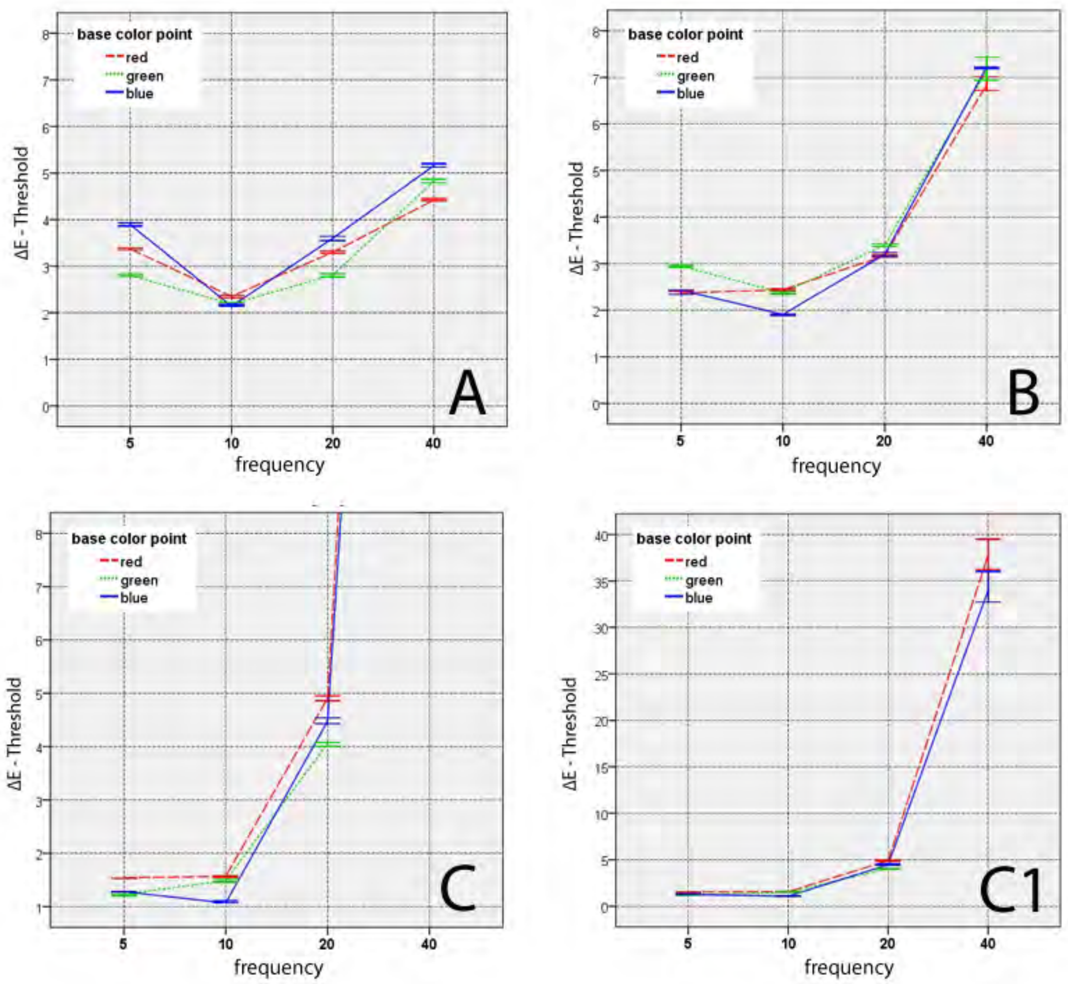

Figure 5.7: Thresholds for lightness changes expressed in $Delta$E a function of frequency for a range of eccentricities: A - 35 deg, B - 60 deg, C - 90 deg, C1 - 90 deg

Chroma Flicker

Figure 5.9 illustrates the results for peripheral Chroma flicker. It shows that, when moving away into the periphery, the less flicker is detected, as the visibility thresholds get larger. The base color point "green" is especially interesting. It can be seen that we are least sensitive to Chroma changes around "green". At 35 and 60 degrees visual thresholds are very large (larger than 60 ΔE), and at 90deg Chroma changes around "green" base point are not detected at all.

"Red" and "blue" base points are relatively close to each other, but it is clear that we are the most sensitive to changes around "blue" base point, especially for the high frequencies. *Figure* 5.9 shows that visibility thresholds at 5Hz and 10Hz are very similar to each other, whereas at higher frequencies this similarity is not present anymore.

ANOVA tests were conducted to check for significances of Chroma flicker effects. The results show that the main effect of eccentricity has a significant effect on peripheral flicker perception, $F(2,4) = 38{,}899$, $p<0.001$, $r = 0{,}747$. Moreover, Tukey post-hoc test confirmed that all eccentricities significantly differ from one another. The main effect of base color was found significant, $F\ (2,4) = 1778{,}053$, $p<0.001$, $r = 0{,}992$. Yet again, all the different base-color points are different from one another. The main effect of frequency is significant, $F(2,4) = 544{,}238$,

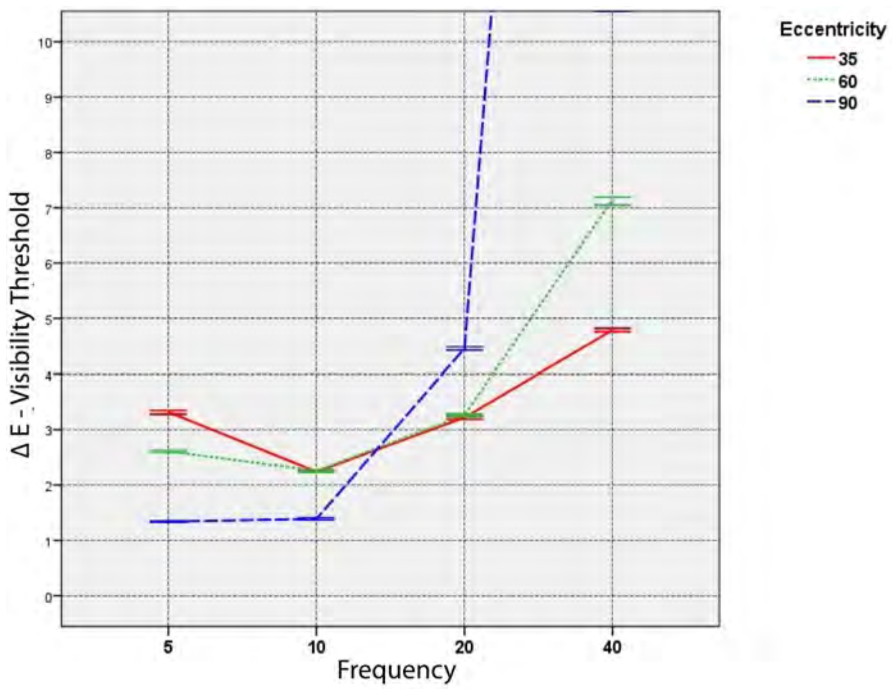

Figure 5.8: Averaged across the base-color points Lightness flicker for different eccentricities as a function of frequency

$p<0.001$, r = 0,973. Post-hoc tests showed that 20Hz is significantly different from all other frequencies; 5Hz and 10Hz were found not to be significant. All the 2-way interactions were tested for and all of them have significant effect on flicker perception. However, their effect size is relatively small and thus does not account for a substantial part of explained variance. The 2-way interaction effects found are presented in *Table* 5.3

Interaction	Statistics
eccentricity x base color point	$F(3,4) = 25{,}598$ $p<0.05$, r = 0,506
eccentricity x frequency	$F(3,4) = 32{,}105$ $p<0.05$, r = 0,553
base color point x frequency	$F(3,4) = 37{,}891$ $p<0.05$, r = 0,587

Table 5.3: Chroma flicker: 2-way interaction effects

hue flicker

Figure 5.10 illustrates the results of hue flicker. It was found before that visibility thresholds are the largest around "green" base point for Chroma flicker. Surprisingly, that is not the case for hue flicker. *Figure* 5.10 shows that the largest thresholds for hue changes are around "red" base color point and, similarly to Chroma changes, the lowest ones are around "blue". The visibility thresholds at 90deg for "red" are so large that they can be neglected. Moreover, it can be read that visibility thresholds at 5Hz are almost the same as at 10Hz, independently of other variables.

ANOVA tests were carried out to check for significance of hue flicker differences. The results show that the main effect of all the tested variables (eccentricity, base color point and frequency) have a significant effect on hue flicker perception in the periphery. All of the effects of these variables have very high size (>0.9). The main effect of eccentricity is $F(2,5) = 855{,}525$, $p<0{,}001$. The post-hoc test confirmed that 90deg is significantly different from both 60deg and

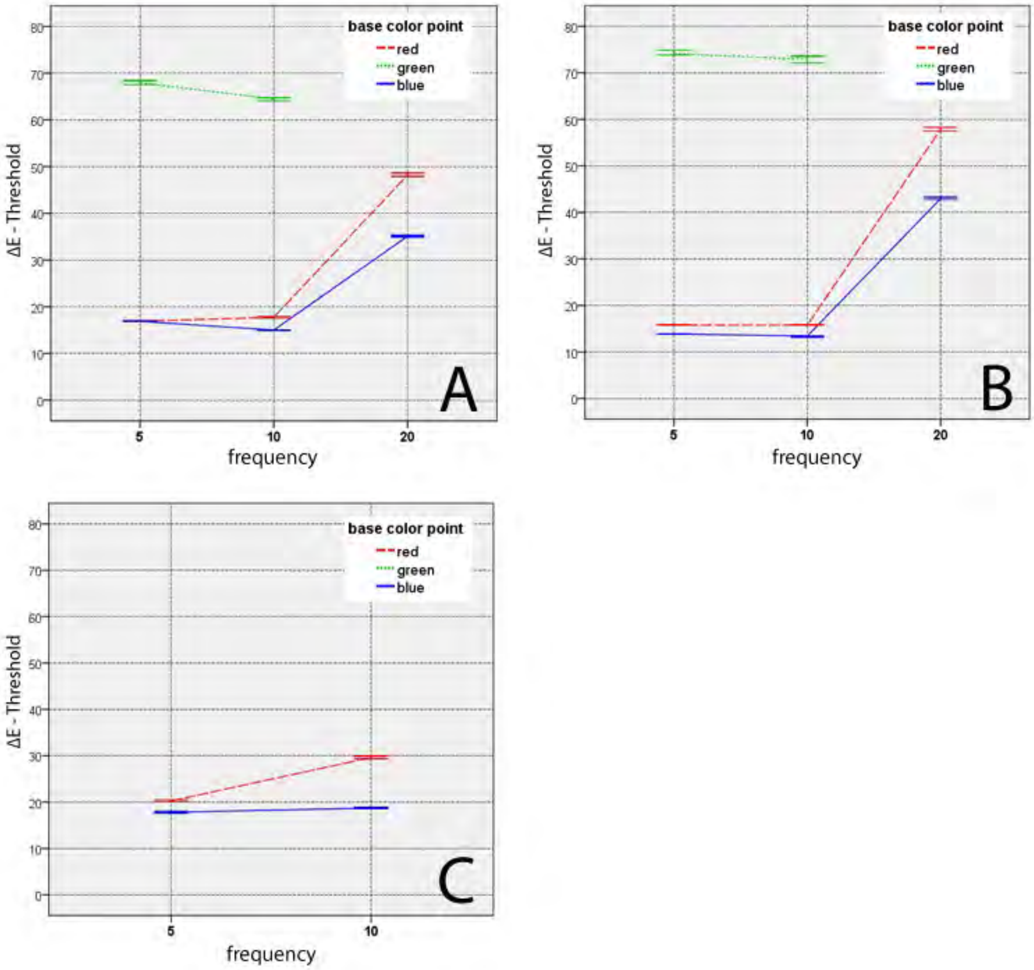

Figure 5.9: Thresholds for chroma changes expressed in ΔE as a function of frequency

35deg, whereas no difference between 60deg and 35deg was found. The main effect of base color point is F(2,5) = 3238,621, p<0,001, and the Tukey tests confirmed that all of the base points are significantly different from one another. Finally, the main effect of frequency is F(3,5) = 1790,699, p<0,001. It was found that 20Hz is significantly different from all other frequencies, whereas no such difference was found between 5Hz and 10Hz. The 2-way interaction effects were tested for and they are summarized in *Table* 5.4. The effect size in each case is above 0.9.

Interaction	Statistics
eccentricity x base color point	F(4,5) = 125,442, p<0,01
eccentricity x frequency	F(4,5) = 93,974, p<0,01
base color point x frequency	F(3,5) = 88,668, p<0,01

Table 5.4: hue flicker: 2-way interaction effects

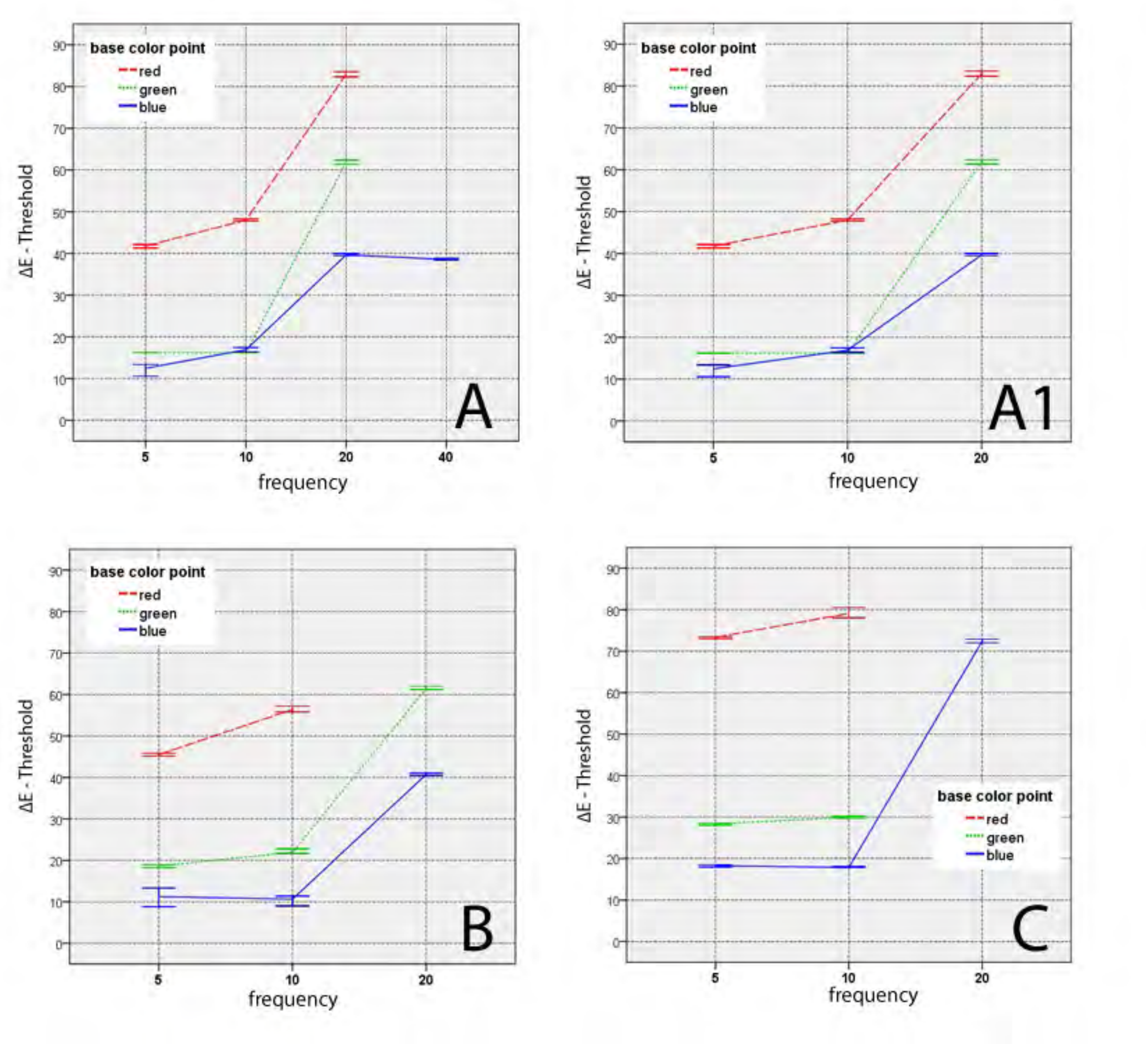

Figure 5.10: Thresholds for hue changes expressed in ΔE as a function of frequency

Experiment 2

Flicker perception in the periphery: the effect of the mental load task

Introduction

Experiment 2 served as a control test for the first experiment. It is important to verify whether the mental load task does indeed impair flicker perception and if so to what extent. Human attention is characterized by the selective properties. It has been found that the more mental load is involved in the task the least sensitive humans get to flicker. This happens because we have limited capacity to perform tasks simultaneously. Therefore, human temporal visual perception depends on the availability of resources. Based on findings of Carmel et al.(2007), it is expected that human flicker sensitivity will increase if the mental load task is removed. The size of this change is, however, unknown and the aim of this experiment is to measure it Carmel et al. (2007).

Method

Participants

Participants were 7 female and 13 male Philips Research employees, aged between 23 and 41 years, with a mean age of 27 years. The conditions for participation were the same as in Experiment 1.

Stimuli, Apparatus and Procedure

The stimuli and apparatus were almost the same as in the Experiment 1. Instead of the mental load task participants were presented with the fixation cross displayed on the screen in front of them. This experiment consisted of only one session, because only one eccentricity, 35 deg, was tested. We assumed that the effect of the mental load is similar across eccentricities. Thus, one eccentricity was sufficient to test the hypothesis. The entire experiment took about half an hour.

ANOVA tests were used to check for significance of the differences resulting from this experiment. Lightness, Chroma and hue were tested separately. The dependent variable was the threshold median, whereas independent variables included: condition (whether the test was conducted with or without mental load task), base color point and frequency.

Results

Lightness Flicker

Figure 6.1 presents visibility thresholds for Lightness flicker as a function of frequency with and without mental load task included. The curve with mental load was replicated from the Experiment 1. It was found in the first experiment that Lightness flicker is independent of the base-color point; therefore the presented curves are averaged across the base points. Inspection of *Figure* 6.1 reveals that the visibility thresholds for Lightness flicker are smaller for the whole range of the frequencies when the subject is not undertaking the mental load task. As before, the highest sensitivity is at 10Hz and Lightness flicker visibility thresholds are almost the same at 5Hz and 20Hz.

It was found that mental load has a significant main effect on Lightness flicker perception, $F(1,6) = 341.347$ $p<0.01$, which confirms that flicker perception is impaired while a participant is subjected to mental workload. As before, a significant effect of frequency has also been found, $F(3,6) = 271{,}750$ $p<0.01$, $r = 0.993$. Tukey post-hoc test revealed that 40Hz is significantly different from all other frequencies. Moreover, 20Hz differs from other frequencies, except for 5Hz. Finally, 5Hz significantly differs from 10Hz. The last variable, base color point has a significant main effect on flicker perception in the periphery, $F(2,6) = 8.919$ $p<0.05$, $r = 0.748$. The effect size is however relatively small here; also the post-hoc tests showed that there is a significant but small difference between "green" and "blue" but not the other ones. Two-way interaction effects were found not to be significant, except "condition x frequency", $F(3,6) = 8{,}380$ $p<0.05$, $r = 0.807$.

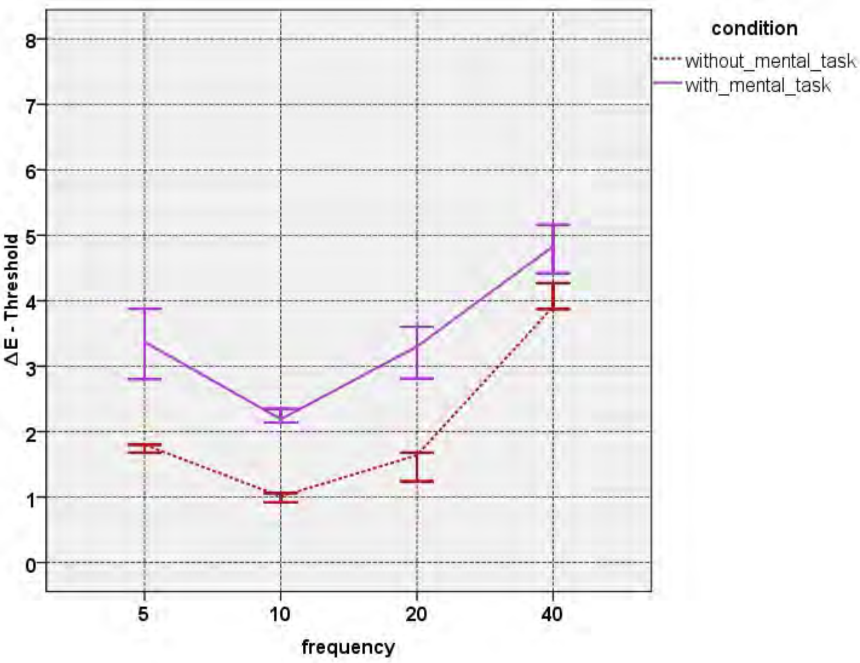

Figure 6.1: Averaged between base-color points thresholds for Lightness changes expressed in *Delta*E as a function of frequency with and without mental load

The purpose of this experiment was to investigate the influence of mental load on flicker perception. In order to calculate the difference between the visibility threshold for flicker perception in the periphery across the two tested conditions (with and without mental task), the Formula 6.1 was used. The ratio between the visibility thresholds for Lightness flicker with and without mental load task was calculated. This ratio is later called the scaling factor.

$$Flickerscalingfactor = \frac{ThresholdWithMentalLoad}{ThresholdWithNoMentalTask} \tag{6.1}$$

Scaling factors calculated for Lightness flicker for each separate frequency are presented in Table 6.1. It was found that the Lightness flicker perception is almost independent on the base-color point; therefore the factors calculated are common for "red", "green" and "blue". Inspection of Table 6.1 reveals that the factors for 5Hz, 10Hz and 20Hz are very similar to one another. Therefore, their mean was calculated and *2.09* was obtained. The scaling factor for frequencies larger and equal to 40Hz is *1.2*.

Frequency (Hz)	Scaling Factor	SD	SE
5	1.9	0.24	0.14
10	2.24	0.08	0.05
20	2.14	0.13	0.07
40	1.2	0.05	0.03

Table 6.1: Lightness Flicker Scaling Factors for Different Base Color Points

Chroma Flicker

Figure 6.2 presents the findings from Experiment 2 for Chroma flicker. The curve for the condition with mental load was replicated from the Experiment 1. This figure shows that the two conditions (with and without mental load task) differ from each other. It is apparent, that the "green" base-color point is very distinct from the other two base points. First, its visibility threshold is the largest one. Second, visibility threshold around "green" changes the most between the two condition. It indicates, that the mental load impairs flicker perception the most for "green" base color point when color is varied in Chroma direction.

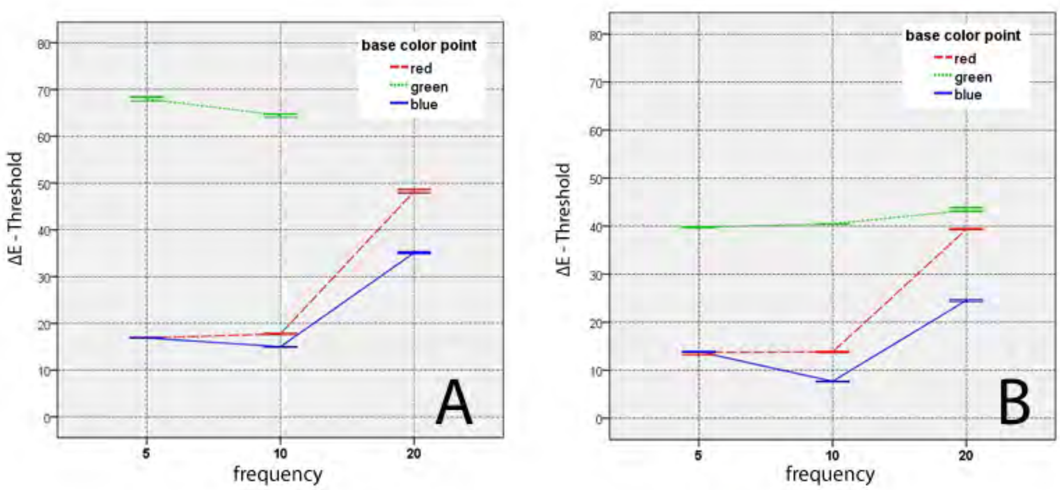

Figure 6.2: Thresholds for chroma changes expressed in ΔE as a function of frequency, A: with mental load, B: without mental load

Anova was used to test for significance of the differences. The main effect of condition was found to have a significant effect on flicker perception, $F(1,3) = 187{,}640$, $p<0.01$. It means that indeed mental load impairs flicker perception. Pairwise comparison confirmed this finding.

The attempts were taken to find the scaling factor for Chroma flicker. Contrary to changes in Lightness, Chroma flicker is dependent on the base-color point. It was found that mental load has different effect on different chromaticities. For that reasons, scaling factor for Chroma flicker was not found.

Experiment 3

Flicker perception in peripheral and central vision

Introduction

Experiment 3 served as a control test for the Experiment 1. Previous study by Sekulovski et al. (2007) already defined the flicker sensitivity in the central vision. However, methods they used differed significantly from the ones in the current study. The total light level we used here was much higher. Moreover, participant were looking directly into the light source (through the diffuser), whereas in the previous research they were investigating the light's reflection on the wall. Due to these differences no direct comparison can be done between these two studies. It was repeatedly demonstrated that, when moving away from the central into peripheral vision, the ability to discriminate colors deteriorates. This is due to the human retinal structure. When the stimuli size is increased, the color discrimination at different eccentricities is almost constant. However, in the current research, the stimuli size is kept constant. Thus, it is hypothesized that visibility thresholds for Chroma and hue flicker are larger in the periphery as compared to the central vision. Moreland (1972); Kayser and Boynton (1996); Nagy and Wolf (1993) Human retina contains both rods and cones, and the number of the first ones increase when moving away from the fovea. Rods are better motion detectors. Moreover, according to Tyler and Hamer (1990) 35 deg eccentricity corresponds to the retinal region of the highest flicker sensitivity. Therefore, it could be expected that Lightness flicker is easier detectable in the peripheral vision. On the other hand it was demonstrated that rods cannot modulate signals in time faster than about 10Hz - 15Hz, which makes them relatively slow in detecting flicker at high frequencies. Thus, it is hypothesized that lightness flicker sensitivity is highest in central vision for high frequencies; whereas for low frequencies it is highest in the peripheral vision, at 35deg Walberg (2005).

Method

Participants

Participants were 9 female and 11 male Philips Research employees, aged between 23 and 51 years, with a mean age of 29 years. The conditions for participation were the same as in Experiment 1.

Stimuli, Apparatus and Procedure

In the Experiment 3 the stimuli and apparatus were almost the same as in the Experiment 1. The centra, and not peripheral vision was tested here. Therefore, the display with mental load task was removed from in front of the participant, and instead the lamp source was placed there. The size of the lamp was also changed. In the Experiments 1 and 2 it was 100 cm tall and 25 cm wide. However, when looking centrally into this kind of light source from the distance of 2,5 meters, its upper and lower parts project also into peripheral retina. Thus, the size of the lamp was reduced to the 35 cm tall and 25 cm wide. This experiment, similarly to the Experiment 2, consisted of only one session. Participants were asked to detect flickering light while looking centrally into into it through the diffuser. The entire experiment took about half an hour. As before, ANOVA tests were conducted to check for significances of the resulting differences. Lightness and Chroma flicker were tested separately. The dependent variable was median threshold; independent variables included: visual angle (0deg and 35deg), base color point and frequency.

Results

Lightness Flicker

Findings from Experiment 3 for Lightness flicker are presented on *Figure* 7.1. The lower curve represents flicker sensitivity for central vision, whereas the upper curve is for peripheral flicker (35 degrees). Both curves are averaged across the base-point because Lightness flicker is chromaticity independent. The curve for peripheral vision was replicated from the Experiment 2.

Investigation of *Figure* 7.1 reveals that the visibility thresholds are lower in central vision as compared to peripheral vision for the whole range of frequencies. The curves for both conditions (central and peripheral vision) look almost the same; they slightly decrease from 5Hz to 10Hz, slightly increase up to 20Hz, and from 20Hz on the increase becomes very rapid.

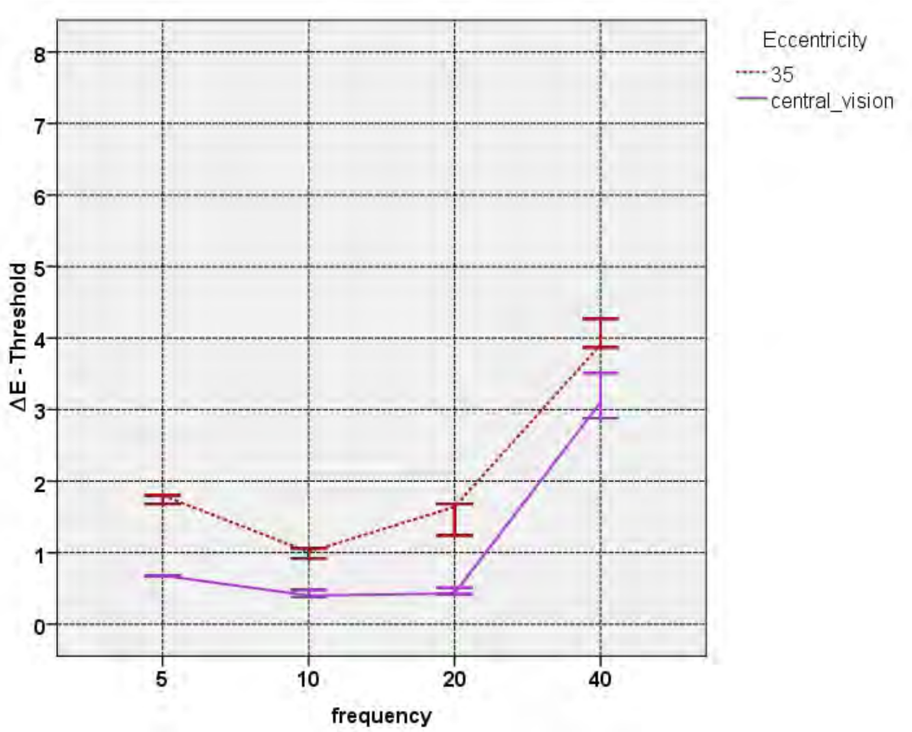

Figure 7.1: Visibility thresholds for Lightness flicker expressed in ΔE for peripheral (35 degrees) and central vision as a function of frequency

The main effect of visual angle on the flicker perception was found to have a significant effect, $F(1,6) = 158{,}205$, $p<0.01$. Pairwise comparisons confirmed that these two conditions significantly differ from each other. Lightness flicker perception in central and peripheral vision was found be independent of the base-color point, as ANOVA test found its main effect to not be significant. The effect of frequency on flicker perception is significant, $F(3,6) = 347{,}772$, $p<0.01$. Tuckey post-hoc test showed that 40Hz is significantly different from all the other frequencies. 5Hz is different from 10Hz; however the rest of the frequencies are not significantly different from one another. The 2-way interaction effects were checked for, but they all were found not to be significant.

Similarly to Experiment 2, scaling factors were calculated to measure the effect of visual angle on flicker perception. Formula 7.1 was used to measure how much central vision differs from the peripheral vision (35 degrees) when no mental load is included. Values for 35deg were replicated from the second experiment.

$$Scaling factor = \frac{ThresholdForPeripheralVision(35degrees)}{ThresholdForCentralVision} \quad (7.1)$$

Scaling factors found for separate frequencies are presented in Table 7.1. Lightness flicker perception is almost independent on base color point and therefore scaling factors are calculated for all of them together. It can be read from this table that scaling factors for frequencies 5Hz and 10Hz are very similar. Therefore, their mean has been calculated, and obtained number, *2,5* is a scaling factor for low frequencies.

Frequency (Hz)	Scaling Factor	SD	SE
5	2.6	0.11	0.1
10	2.38	0.16	0.1
20	3.36	0.51	0.3
40	1.28	0.19	0.11

Table 7.1: Lightness flicker Scaling Factors for the difference between central and peripheral vision

In the second experiment scaling factor for calculating lightness flicker visibility threshold without mental task (when the visibility threshold under mental load is given) was obtained. We applied this factor to the lightness flicker at 90 degrees and further compared it against flicker thresholds in central vision. It is illustrated at *Figure* 7.2. This figure reveals that visibility thresholds in far periphery for low frequencies (5 and 10Hz) are almost as low as in central vision. With the increasing frequency the difference between central and peripheral vision becomes very large.

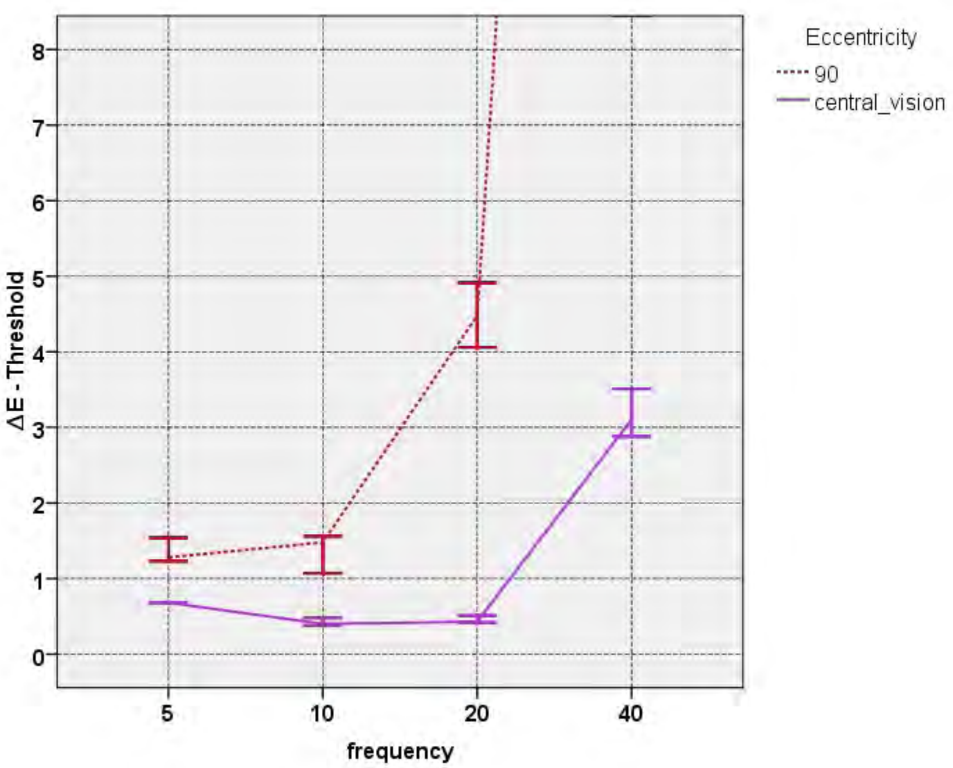

Figure 7.2: Lightness flicker for central and far peripheral vision without mental load

Chroma Flicker

Figure 7.3 illustrates results for Chroma flicker perception in central and peripheral vision (35deg). It can be seen that in central vision the visibility thresholds are much lower than in the periphery. Moreover, different base-color points change differently when moving away from central vision. "Green" changes from about 6,5 ΔE in the central vision to as much as 40ΔE at 35deg eccentricity. The change of "blue" and "red" is not as large as in the case of "green".

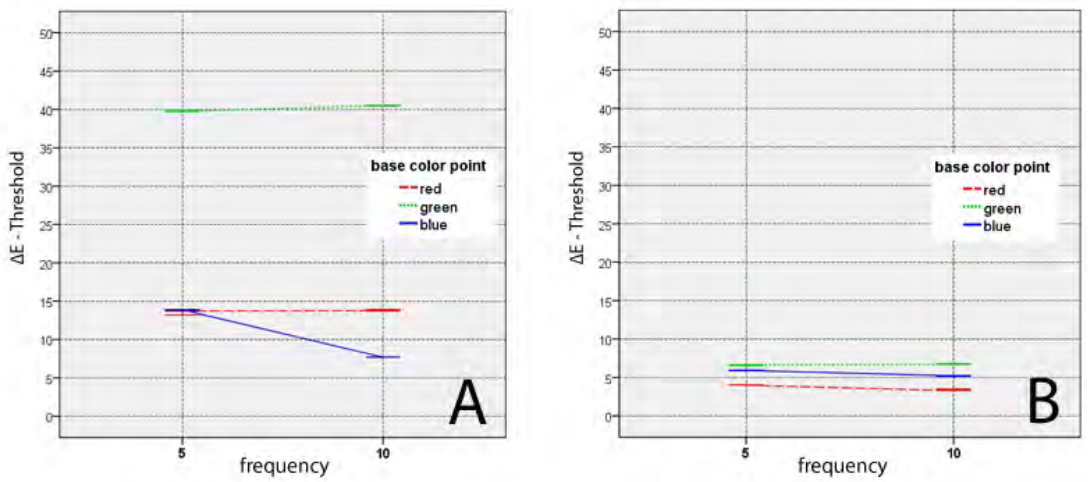

Figure 7.3: Thresholds for chroma changes expressed in ΔE as a function of frequency: A: peripheral vision (35ged) B: central vision

The main effect of visual angle was found to have a significant effect on Chroma flicker perception, F(1,2) = 245,513, p<0.01. Base-color point was found to have a significant effect on flicker perception, F(2,2) = 92,623, p<0.05. Tukey post-hoc test confirmed that "green" is significantly different from both "blue" and "red"; however "red" is not different from "blue". Frequency was found not to be significant. 2-way interaction effects were checked for and "angle x base color" was found to be significant, F(2,2) = 70,526, p<0.05. Other interaction effects were not significant.

Discussion

In the current study we investigated human flicker perception in the peripheral vision under mental load. We found flicker visibility thresholds for different base color points (red, green and blue), directions of change Lightness, Chroma and hue) and eccentricities (35deg, 60deg and 90deg) as a function of frequency. The effect of mental load on flicker perception was tested. Finally, we compared peripheral with central vision. The main findings are summarized and discussed below.

In the first experiment the peripheral flicker sensitivity under mental load was tested. First, it was hypothesized that flicker sensitivity gets impaired with increasing eccentricities. This assumption holds only for Chroma and hue flicker. The further into the periphery the less flicker, along these two axes, is detected. If the flicker amplitudes are large enough, some Chroma and hue changes can be perceived even at as large visual angles as 90 degrees. This is in line with what was expected based on human retinal structure and a study of Hansen et al. (2009). They argued that cone-opponent channels, however sparse, are still present at very large visual angles. It is a possible explanation for the finding that Chroma and hue flicker can still be perceived at very far periphery. However, it is more probable explanation that it could be due to the rod interactions (Hansen et al., 2009).

Further, it was found that Lightness flicker is independent of the base-color point for all the eccentricities and frequencies used in this experiment. It is in line with what was expected, as the same was found in a study by Sekulovski et al. (2007), who tested human flicker sensitivity in central vision. In the second experiment the mental load was removed. The results show that Lightness flicker is independent of the base-color point regardless of the presence or absence of the mental load. This is an important finding, especially for the lighting application developers. It is because the chromaticity of the base-color point can be ignored when only Lightness changes are considered within a given application (Sekulovski, 2007).

An interesting difference in sensitivity to Lightness flicker for different eccentricities was found. For low frequencies we are more sensitive to Lightness changes at large eccentricities, whereas for high frequencies we are more sensitive to Lightness changes at near eccentricities. Previous studies by Tayler & Hammer (1990) indicated that the retinal region of the highest flicker sensitivity is 35 degrees. In the current study however, 35 degrees is not always the eccentricity of the highest sensitivity. Most of the previous works on the subject, including the study of Tayler & Hammer (1990), investigated flicker sensitivity in terms of Critical Fusion Frequency. However, such an approach does not provide information on flicker sensitivity at different frequencies. In the current research 90 degrees curve is the steepest whereas 35 degree is the shallowest one. After interpolating these curves, we can compute CFF and it is indeed the highest for 35 deg. However, CFF alone cannot be the basis for saying that we are most sensitive to flicker at this eccentricity, as CFF does not contain the complete information. As shown in this study, humans have different sensitivity to lightness flicker at different frequencies. It is again important when developing dynamic lighting applications. Depending on the hardware parameters, e.g. frequency of change, one should take into account the different sensitivity at different frequencies (Tyler and Hamer, 1990).

The very high sensitivity to Lightness flicker for low frequencies (5Hz and 10Hz) at 90 degrees is explained with the fact that rods are able to detect faint light, but the signals can be modulated in time only about 10 - 15 Hz and not faster. Apparently, the speed at which signal is modulated by the rods plays an important role here.

Further, it was hypothesized that sensitivity to Lightness flicker peaks around 10Hz. For small eccentricities (35 and 60 degrees) this peak was found at 10Hz, confirming the findings by Walberg (2005). On the other hand, with the increasing eccentricity this peak seems to gradually disappear, and at 90 degrees there is no peak at the frequencies which were tested.

However, such peak may exist for frequencies which were not chosen in this test (e.g. 7,5Hz). It is therefore recommended to test more frequencies so that the maximum value for every eccentricity is found (Walberg, 2005).

Sekulovski et al. (2007) found that in the central vision Lightness changes are more visible than changes in Chroma and hue. Previous studies on this subject are very limited, but similar results were expected. It was discovered that we see more of a Lightness flicker than of Chroma and hue in the periphery. When moving away into the far periphery these differences get even larger.It is explained with the fact that with the increasing eccentricity cones in the human retina, which are responsible for color vision, become less dense (Sekulovski, 2007).

Current study demonstrates that the model developed for central vision is not perfectly suitable to predict outcomes in the periphery. Chroma changes around ”green” base-color point are hardly perceivable, and at very large eccentricities (90 deg) we fail to detect them entirely. What is also surprising, changes around ”blue” and ”red” can still be detected for small frequencies even at very large eccentricities. In case of hue flicker, it was found that we are the least sensitive to changes around the ”red” base-color point. At large eccentricities (90deg) visibility threshold around ”red” is so large that it can be neglected. However, changes around ”blue” and ”green” can still be detected. One of the possible explanations for such behavior of Chroma and hue changes is that in the periphery these are not pure chroma and hue changes but some Lightness components are also included. Most probably, the dimensions in the used model are shifted and hence the unusual changes are produced. Development of the model for peripheral vision could facilitate future predictions of chromatic flicker. Moreover, the color was varied within CIE LCh color space; therefore large amplitude hue flicker alternates its color completely. For example, change around the ”green” base-color point goes as far in the color space, that a subject perceives alternating ”cyan-ish” and ”pink-ish” and no green. Surely, it influenced the hue flicker perception substantially.

The above findings have their use in lighting applications: when moving away into the periphery colored light perception gets impaired and chromatic flicker requires large amplitudes to be detected. As demonstrated before, colors also get desaturated. Consequently in peripheral dynamic lighting applications colors used can be less saturated and changes can have larger amplitudes, which obviously is a more economic solution.

In the second experiment the mental load was removed and the results were compared against the experiment where mental load was present. In line with the load theory and findings of Carmen et al. (2007), it was found that mental load significantly impairs flicker perception at all frequencies. Only one eccentricity, 35deg, was tested, but we expected that this finding holds for every visual angle. A scaling factor for lightness flicker was found. The mental task used in the current study had relatively low load (for the exact description of the mental load task used see Chapter 5). If the mental load is increased it may be the case that the flicker sensitivity is decreased. Carmel et al.(2007) demonstrated that when the mental load is increased the ability to detect flicker in decreased because of the humans' attention capacity limitations. It is interesting that mental load impairs Chroma flicker perception mostly around the ”green” base-color point. It is however difficult to provide an explanation for this finding. (Carmel et al., 2007)

In the last experiment, it was found that flicker sensitivity is higher in central than in peripheral vision for all measured frequencies. It was not possible to conduct a detection experiment in central vision together with the mental load (for explanation see Method section) and thus the detection without mental load was carried out. Therefore, it was compared with the results from the 35 degrees angle where also no mental task was included. We expected that sensitivity to lightness flicker is the highest at 35 degrees and not in the central vision. It was found that human flicker sensitivity is highest in central vision for all the measured frequencies. However, the extrapolation of the results shows that Critical Fusion Frequency is higher at 35 which is in line with the previous studies. (Tyler and Hamer, 1990)

In the second experiment we found a scaling factor for 35 degrees, which calculates lightness visibility threshold without mental load, when threshold under mental load is given. Under the assumption that this scaling factor is accurate, one can apply it to calculate the Lightness flicker perception with no mental load for all other eccentricities. After doing this for 90 degrees it can be seen that low-frequency Lightness flicker sensitivity at 90 degrees is almost as high as in the central vision. However, these results should be treated with special care and more research should be conducted to verify whether the scaling factor can be generalize across different eccentricities and frequencies. In terms of practical dynamic lighting applications it is important to realize that we are similarly sensitive to Lightness flicker at low frequencies in central vision and far periphery. All the other in-between eccentricities can include larger flicker amplitudes and the Lightness flicker cannot be detected anyway.

The current study is of a very fundamental character. It showed that the color space developed for central vision may not be suitable for predicting outcomes in the peripheral vision. On the other hand, many meaningful findings were obtained. Therefore, the current research lays basis for creating a model for temporal changes in human peripheral vision. In order to create such a model, more work on the subject is required. The current study is especially important, because it explores flicker sensitivity at a whole range of frequencies and visual angles. Previous work focused mainly on CFF and eccentricities up to only 50 degrees. CFF is however not a sufficient indicator of human flicker sensitivity, as it only considers the highest frequency at which we are still able to detect flickering light in the optimal conditions.

Findings from this research can be used to improve perceived attractiveness in a series of LEDs based application. LEDs are digital and so they produce colored light in discrete steps at discrete time intervals. It is important that these discrete changes do not produce undesirable outcomes, such as flicker. The implementation of the current findings helps us to eliminate such effects. Peripheral vision differs significantly from central vision. It is important because lighting applications usually serve as a background for other applications and therefore they are very often perceived in the periphery. The main challenge in the design and control of the dynamic lighting systems, namely the produced attractiveness, can be improved with the use of the current findings.

Limitations and Recommendations

In some of the previous studies on peripheral vision, researchers dilitated the pupil of their participants, so that its size is kept constant across the eccentricities. It is an understanding approach, because with changing eccentricity different amount of light is reaching human eye, and so the pupil size varies as well. However, the current project aims at very practical application, and thus we did not dilitate participants pupil because it does not have much added value. However, in the future, it is recommended to consider such an approach.

In the current study the LCh color space was used. It is a color space developed and used for central and not peripheral vision. When moving into the periphery rods are getting denser and cones less dense. When changing from the day in to the night vision we also change into rod vision. When looking at the scotopic efficiancy curve, one can easily realize that it is shifted into the green spectrum. It may be therefore the case, that for the peripheral vision, colors are not detected at all, but what is detected is the lightness change. The axes are shifted in the peripheral vision, hence the discrepancy. It is highly recommended to conduct more research and as a result to develop a model for peripheral color vision. Such a model could predict not only chromatic flicker peripheral sensitivity but any other color-related challenges.

Mental load used in this experiment was relatively low. The increase of mental load can however be easily achieved my manipulating the number and speed of the small black balls in the task that was created. The more balls there are and the faster they are the more attention is required to handle the task successfully and consequently the less attention can be devoted to flicker detection. Through manipulation of the mental load task it can be found what are flicker visibility thresholds for different load levels, and how much mental load is required for flicker to become not perceivable at all. It is therefore recommended to quantify the mental task. It can be easily achieved with the Mental Effort Scale created by Zijlstra and Van Doorn (1985). Once, the mental load task is quantified, the relation between different levels of mental load and peripheral flicker perception can be measured. (Zijlstra and Van Doorn, 1985)

Conclusions

The presented study shows what is human flicker perception in the peripheral vision under mental load. Three detection experiments have been conducted, which included one main experiment and two control ones. Through these experiments flicker visibility thresholds for different base color points (red, green and blue), color space dimensions (Lightness, Chroma and hue) and eccentricities (35deg, 60deg and 90deg) as a function of frequency have been found. The main finding are summarized as follows:

- Chroma and hue flicker sensitivity gets impaired with the increasing eccentricities for all frequencies
- Lightness flicker sensitivity gets impared for high frequencies (>20Hz) with increasing eccentricity; for low frequencies (5Hz and 10Hz) lightness flicker sensitivity improves with increasing eccentricity
- Lightness peripheral flicker is independent of a base-color point
- Peripheral flicker sensitivity around ”red” and ”green” base points is worse than that of ”blue”. Moreover, visibility thresholds for Chroma flicker are lower when color is varied around ”red” rather than ”green”, whereas the opposite is valid for hue flicker
- Variations around the ”green” base-color point are virtually undetectable for Chroma flicker in the periphery of human vision
- Sensitivity to peripheral Lightness flicker peaks around 10Hz for small eccentricities (35deg)
- For Chroma and hue flicker visibility thresholds in the periphery are the same for 5Hz and 10Hz frequencies
- Peripheral flicker sensitivity is impaired when mental load in included
- Scaling factor for calculating Lightness flicker without mental load was found: 2.9
- Flicker visibility thresholds are smaller in the central than in the peripheral vision

Bibliography

Abramov, I. and Gordon, J. (1977). Color vision in the peripheral retina. I. Spectral sensitivity. *Journal of the Optical Society of America*, 67(2):195–201.

Alexander, K. and Fishman, G. (1984). Rod-cone interaction in flicker perimetry. *Br. J. Ophthalmol*, 68:303–309.

Anstis, S. (1996). Adaptation to peripheral flicker. *Vision Research*, 36(21):3479–3485.

Ayama, M. and Sakurai, M. (2003). Changes in hue and saturation of chromatic lights presented in the peripheral visual field. *Color Research and Application*, 28(6):413–424.

Beurden, M., IJsselsteijn, W., et al. (2007). Smoothness and flicker perception of temporal color transitions.

Bunting, F. (1988). *The ColorShop Colour Primer: An Introduction to the History of Colour, Colour theory, and Colour Measurement.* Light Source Computer Images, Inc. An X-Rite company.

Carmel, D., Saker, P., Rees, G., and Lavie, N. (2007). Perceptual load modulates conscious flicker perception. *Journal of Vision*, 7(14):14.

Coletta, N. and Adams, A. (1984). Rod-cone interaction in flicker detection. *Vision Research*, 24(10):1333–1340.

Coren, S., Ward, L., and Enns, J. (1994). *Sensation and Perception.* Harcourt Brace College Publishers.

Fairchild, M. (2005). *Color appearance models.* Wiley.

G.S. Brindley, J. C. and Rushton, W. (1966). The Flicker Fusion Frequency of the Blue-Sensitive Mechanism of Color Vision. *J. Physiol*, 183:497–500.

Hamada, H. and Yujiri, A. (2004). Color Zone Map in peripheral vision at various illuminance levels. *Optical Review*, 11(4):240–248.

Hammett, S. and Smith, A. (1990). Flicker adaptation in the periphery at constant perceived modulation depth. *Perception*, 19(1):113.

Hansen, T., Pracejus, L., and Gegenfurtner, K. (2009). Color perception in the intermediate periphery of the visual field. *Journal of Vision*, 9(4):26.

Kayser, P. and Boynton, R. (1996). *Human color vision.*

Kelly, D. (1974). Spatio-temporal frequency characteristics of color-vision mechanisms. *J. Opt. Soc. Am*, 64:983–990.

Lavie, N. (2005). Distracted and confused?: Selective attention under load. *Trends in Cognitive Sciences*, 9(2):75–82.

Lee, B., Pokorny, J., Smith, V., Martin, P., and Valberg, A. (1990). Luminance and chromatic modulation sensitivity of macaque ganglion cells and human observers. *Journal of the Optical Society of America A*, 7(12):2223–2236.

Metha, A. and Mullen, K. (1996). Temporal mechanisms underlying flicker detection and identification for red–green and achromatic stimuli. *Journal of the Optical Society of America A*, 13(10):1969–1980.

Moreland, J. (1972). Peripheral color vision. *Handbook of sensory physiology*, VII/4:517–536.

Moulden, B., Renshaw, J., and Mather, G. (1984). Two channels for flicker in the human visual system. *Perception*, 13(4):387–400.

Mullen, K., Sakurai, M., and Chu, W. (2005). Does L/M cone opponency disappear in human periphery? *Perception*, 34(8):951.

Murray, I., Parry, N., and McKeefry, D. (2006). Cone opponency in the near peripheral retina. *Visual Neuroscience*, 23(3-4):503–507.

Nagy, A. and Wolf, S. (1993). Red-green color discrimination in peripheral vision. *Vision research*, 33(2):235.

Nygaard, R. and Frumkes, T. (1985). Frequency dependence in scotopic flicker sensitivity. *Vision Research*, 25(1):115–127.

Overheim, R. and Wagner, D. (1982). *Light and color*.

Pantle, A. (1971). Flicker adaptation—i. effect on visual sensitivity to temporal fluctuations of light intensity. *Vision Research*, 11, 9:943–952.

Poynton, C. (2003). *Digital Video and HDTV Algorithms and Interfaces*. Morgan Kaufmann Publishers.

Raninen, A., Franssila, R., and Rovamo, J. (1991). Critical flicker frequency to red targets as a function of luminance and flux across the human visual field. *Vision research*, 31(11):1875.

Raninen, A. and Rovamo, J. (1986). Perimetry of critical flicker frequency in human rod and cone vision. *Vision research*, 26(8):1249.

Rovamo, J. and Raninen, A. (1984). Critical flicker frequency and M-scaling of stimulus size and retinal illuminance. *Vision research*, 24(10):1127.

Rovamo, J. and Raninen, A. (1988). Critical flicker frequency as a function of stimulus area and luminance at various eccentricities in human cone vision: a revision of Granit-Harper and Ferry-Porter laws. *Vision research*, 28(7):785.

Sakurai, M., Ayama, M., and Kumagai, T. (2003). Color appearance in the entire visual field: color zone map based on the unique hue component. *Journal of the Optical Society of America A*, 20(11):1997–2009.

Sekulovski, D., V. I. B. M. C. R. (2007). Smoothness and flicker perception of temporal color transitions. *15th Color Imaging Conference*.

Swanson, W., Ueno, T., Smith, V., and Pokorny, J. (1987). Temporal modulation sensitivity and pulse-detection thresholds for chromatic and luminance perturbations. *J. Opt. Soc. Am. A*, 4:1992–2005.

Tkalcic, M. and Tasic, J. (2003). Colour spaces-perceptual, historical and applicational background. pages 304–308.

Tyler, C. (1981). Specific deficits of flicker sensitivity in glaucoma and ocular hypertension. *Investigative Ophthalmology & Visual Science*, 20:204–212.

Tyler, C. (1985). Analysis of visual modulation sensitivity. II. Peripheral retina and the role of photoreceptor dimensions. *Journal of the Optical Society of America A*, 2(3):393–398.

Tyler, C. (1987). Analysis of visual modulation sensitivity. III. Meridional variations in peripheral flicker sensitivity. *J. Opt. Soc. Am. A*, 4:1612–1619.

Tyler, C. and Hamer, R. (1990). Analysis of visual modulation sensitivity. IV. Validity of the Ferry-Porter law. *Journal of the Optical Society of America A*, 7(4):743–758.

van der Horst, G. (1969). Chromatic flicker. *Journal of the Optical Society of America*, 59(9):1213.

Walberg, A. (2005). *Light Vision Color*. John Wiley & Sons, Ltd.

Watson, A. (1986). *Temporal sensitivity*, volume 1.

Zijlstra, F. and Van Doorn, L. (1985). The construction of a subjective effort scale. *Delft: Delft University of Technology, report.*