Master in Computational Colour and Spectral Imaging (COSI)

Effect of Luminance Adaptation on Contrast Threshold in HVS

Master Thesis Report

Presented by

Akash Harijan

and defended at the

Norwegian University of Science and Technology

September 2023

Academic Supervisor(s): Dr. Giorgio Trumpy, Dr. Steven Yves Le Moan

Jury Committee:

1. Dr. Damien Muselet, Jean Monnet University, France.
2. Dr. Piotr Bartczak, University of Eastern Finland, Finland.

Submission of the thesis: 10th August 2023
Day of the oral defense: 5th September 2023

Abstract

A psychophysical experiment was conducted to investigate the effect of surround luminance i.e. luminance out of 10° visual angle of the retina, on luminance contrast in foveal view by the human visual system (HVS) on a high dynamic range (HDR) display having a maximum 1000 cd/m^2 luminance. The stimulus modified Landolt C was presented on display at a visual angle of 2°, with the observer positioned 40 cm away from the display, whereas a dark black circle with minimum luminance (0.03 cd/m^2) was employed within a visual angle of 10° on display as background, and the display's rest of pixel area as a surrounding. The experiment employed multiple luminance scales of the surrounding, encompassing both achromatic color and chromatic colors such as red, green, blue, yellow, cyan, and magenta. The experiment involved a total of thirty participants, 19 males and 11 females, who were tasked with recognizing the orientation of stimulus openings to determine the luminance thresholds of their vision in various surrounding colors using a threshold and matching method based psychophysical experiment, specifically focusing on luminance adaptation.

The experiment's findings showed that red surround color has the most impact on luminance adaption compared to all other surround colors, whereas blue and yellow surround color has the least impact. It was discovered that observers had the lowest consistency in the red surround color, they required the highest number of stimuli to attain a particular threshold, and they spent the most time on red surround based stimuli overall, indicating that it was challenging for observers to discern contrast in the red surround color. Contrarily, blue showed more consistent responses from observers, required the fewest stimuli to reach the threshold, and required the least overall time to process stimuli, indicating that it was not difficult to notice the contrast in the blue surrounding color. Additionally, it was observed that, with the exception of white, blue, and yellow surround colors, the longer time an observer spent in a certain surround color, the more luminance adapted it became to that surround color. Moreover, this experiment also produced byproduct results like vertical and horizontal perception, and it was discovered that HVS perceive vertical direction gratings better than horizontal ones. These results can be valuable to design or evaluate the color appearance models. The Matlab code used for this experiment is uploaded on GitHub LuminanceAdaptation.

Acknowledgment

- I would like to extend my sincere gratitude to the divine entity, Almighty Allah, for providing guidance throughout a transformative and challenging academic endeavour, resulting in the successful completion of my thesis.

- I express sincere gratitude towards my supervisors, Dr. Giorgio Trumpy and Dr. Steven Yves Le Moan, whose invaluable mentorship and unwavering support have not only influenced my academic pursuits but also served as a source of inspiration. I extend my heartfelt gratitude to Jana Blahova for her tireless efforts in ensuring NTNU Colorlab accessibility and seamless operations, that has greatly facilitated the progress of my dissertation journey.

- I am thankful to my family, the unwavering faith displayed by my family has served as a consistent source of support throughout the entirety of my master's programme, providing firm strength during times of difficulties.

- I express my profound appreciation for invaluable support and steadfast companionship during challenging circumstances to all my esteemed peers in the COSI programme, with a special mention to Ehsan Ullah, Aqsa Hassan, and Syed Ali Raza.

- I express profound gratitude towards the European Union and the COSI consortium for hosting me and giving me the opportunity to cultivate and thrive.

Acronyms

APL	Average picture level
CFF	Critical flashing frequency
CRT	Cathode ray tube
CSF	Contrast sensitivity function
DMD	Digital micro-mirror devices
EOCF	Electro-optic conversion curve
HDR	High dynamic range
HLG	Hybrid log gamma
H-K	Helmholtz-Kohlrausch
HVS	Human visual system
IES	Illuminating Engineering Society of North America
JNDs	Just noticeable contrast differences
LCD	Liquid crystal display
LCoS	Liquid crystal on silicon
LDR	Low dynamic range
LEDs	Light emitting diodes
OLED	Organic light emitting diodes
PQ	Perceptual quantization
RMSE	Root mean square error
SDR	Standrad dyamic range

Contents

1 | Introduction

Well begun is half done.

Aristotle

Nature has served a great inspiration for human innovations, even a huge number of so called human inventions were imitated from nature. Same is the case when it comes to display technologies, which draw significant inspiration from the Human Visual System (HVS). The sensory function of vision is commonly acknowledged as a highly intricate and complex process performed by the human brain, given that a significant portion of the human brain is devoted to the visual system Poot (2000). It includes an array of intricate processes that operate together, including motion detection, object recognition, and color vision. It is organised into a series of distinct steps, with each step dedicated to a specific task that allows the processing of visual input. Initial step that transforms the visual input is a neural network, commonly called retina Poot (2000), and during this step a particular process known as light adaptation is applied and this whole thesis revolves around the process of light adaptation, also known as luminance adaptation.

Luminance adaptation is an innate ability of HVS that changes the sensitivity of visual system to different lighting conditions and lighting scales. Under natural circumstances, ambient light level can vary by a factor of about 10 log units Shapley and Enroth-Cugell (1984), where as the biological hardware system in not capable of such a high dynamic range Shapley and Enroth-Cugell (1984). Therefore, it is crucial to regularly modify the sensitivity of the system in order to optimise the transmission of information from the visual input to the brain. The presence of this adaptive mechanism serves to prevent the drowning of small signals by neuronal noise, as well as the saturation of large signals Poot (2000). The process of light adaptation plays a crucial role in preserving the ability of retinal neurons to respond to visual stimuli that change quickly, ensuring that the response remains within the dynamic range. This allows for a balanced and optimal processing of visual information Poot (2000).

One commonly used approach to understand the concept of luminance adaptation is through the field of psychophysics, where, changes are made to the stimulus in such a way that these stimulus changes allow an understanding of the corresponding changes in visual response, which helps in the understanding of various phenomena within the visual system. Therefore, a psychophysical study was conducted in this research to understand effect of luminance adaptation on contrast thresholds on a high dynamic range (HDR) display, as normal display systems lack the capability to achieve a dynamic range that is comparable to the HVS. A luminance contrast is a difference between two luminances. Extensive research has been conducted on both subjects individually King-Smith and Carden (1976); Krauskopf (1980); Spillmann and Conlon (1972), as well as their combination Chen et al. (2005); Sloane et al. (1988), in the context of HVS. However, a significant knowledge gap still remains, necessitating further investigation to achieve a comprehensive understanding of these phenomena in HVS. In this thesis, a psychophysical experiment was conducted to understand better the phenomenon of luminance adaptation in both chromatic and achromatic conditions.

This section provides further details about the research context, motivation, research gap, contributions and thesis outline below. Moreover, it is worth mentioning that AI tools were used in this thesis. ChatGPT was used as search engine for general queries, to get sample codes to generate graphs. Quiltbot was used to check grammatical mistakes and restructuring of some sentences.

1.1 Research context

A thorough understanding of HVS, particularly the process of luminance adaptation is an important phenomenon across multiple scientific disciplines, including color science Loomis and Berger (1979), psychology Adelson and Jonides (1980), neuroscience Werblin (1971), and cognitive sciences Weisstein (1970). The ever increasing prevalence of digital images and their realistic representation on displays has sparked intensive research in display technologies. The emergence of HDR displays has further intensified investigations into capturing, creating, and representing HDR scenes. Luminance adaptation plays a crucial role in the development of HDR technologies, enabling the display of high luminance scenes in a manner that reduces eye strain, enhances readability, and provides more comfortable viewing experiences, considering the adapting screen brightness, contrast, and ambient light conditions Ledda et al. (2004); Mantiuk et al. (2004). This knowledge can also lead to improved screen designs for various devices Poot (2000).

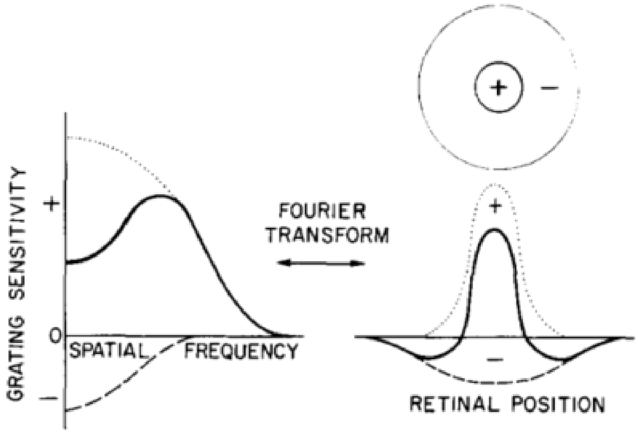


Figure 1.1: *Relationship between contrast sensitivity function and a Gaussian curve Kelly (1977).*

Additionally, luminance adaptation significantly influences appearance of color, affecting the way the HVS perceives color under different lighting conditions Akyüz and Reinhard (2006). It has a notable impact on the perceived brightness of color, particularly during transitions between bright and dark environments. Luminance adaptation is a vital aspect of color constancy, as it influences how the HVS discounts the illuminant's color and focuses on the object's inherent color Foster (2011). Furthermore, it plays a pivotal role in color appearance models, which are mathematical models aiming to predict how color will be perceived by human observers in diverse environments with varying illumination levels Moroney et al. (2002). Understanding luminance adaptation is essential for advancing our knowledge of human vision and developing technologies that enhance our visual experiences and interactions with the digital world.

1.2 Motivation

The focus of this thesis revolves around luminance adaptation, and it has been determined that Gaussian filters provide a reliable approximation of HVS adaptation in relation to visual angle. In their iCAM06 model, Kuang et al. (2007) employed a low-pass Gaussian filter on the scene luminance image to estimate the local light adaptation of the scene. Yamaguchi and Fairchild (2004) conducted a study on the determination of the size of the Gaussian filter. They proposed that the variance of the Gaussian filter should be adjusted to correspond with a 5° angular view of the scene. In a recent psychophysical study conducted by Sun et al. (2017), Gaussian filters were employed to estimate the luminance of the adapting field with adjusting the standard deviation values of Gaussian curve. Furthermore, Kelly (1977) conducted a study on the relationship between luminance adaptation and retinal position as shown in Figure 1.1. The findings of this study revealed that a Gaussian curve provides a reliable estimation of luminance adaptation. Additionally, it was discovered that by employing Fourier transform on the contrast sensitivity function, it is possible to obtain a Gaussian curve, as illustrated in Figure 1.1.

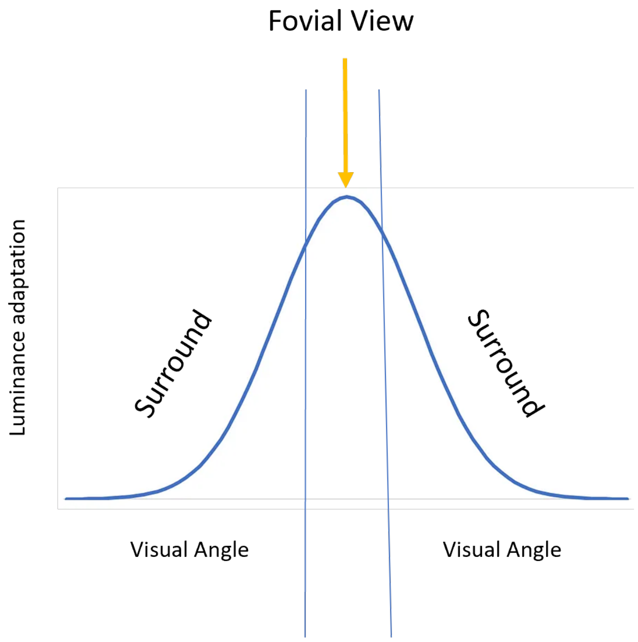
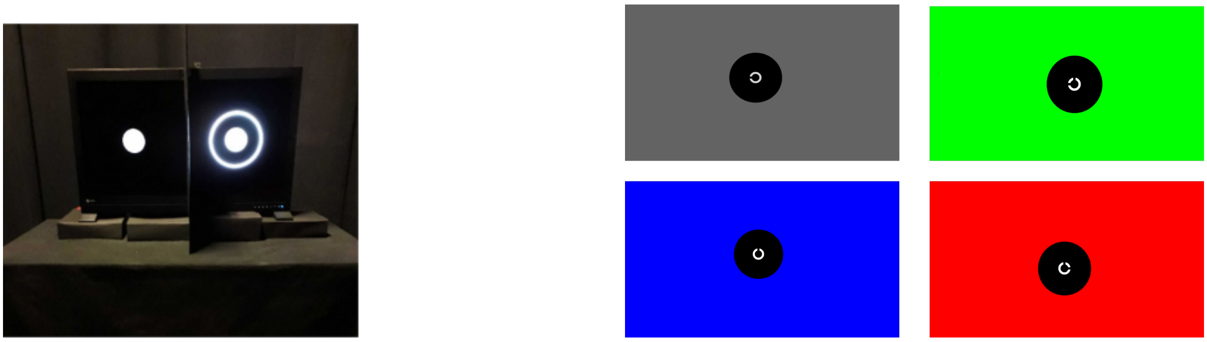


Figure 1.2: *A Gaussian curve and how it represents the luminance adaptation.*

Furthermore, Kelly (1977) conducted a study that examined the relationship between the degree of adaptation in the retina and the Gaussian curve. The Gaussian curve, characterised by a bell-shaped distribution, was found to accurately represent the adaptation levels. Specifically, the peak of the curve corresponds to the foveal view, where the degree of adaptation in the HVS is highest as depicted in Figure 1.2, the degree of adaptation gradually decreases in the surrounding areas of the foveal view. In most psychophysical studies Shapley and Enroth-Cugell (1984); Laughlin (1989), that related to luminance adaptation, adaptation of foveal view is studied, and how it affects the perception in HVS, but the main motivation of this research is to explore the degree of adaption of surrounding of foveal view instead of the foveal view itself and how this surround adaptation affects the perception of the contrast.



((a)) *Unrelated color used as background in previous studiesPhung et al. (2022).*

((b)) *Related colors used as surround in psychophysical study conducted in this thesis work.*

Figure 1.3: *Unrelated and related colors used as background or surround in the psychophysical studies.*

1.3 Research gaps

This study has tried to answer some of the questions raised in above Section 1.2.

1. **[R1]**: Luminance adaptation is approximated by a Gaussian like function, and majority of adaptation takes place at the peak of bell curve of Gaussian function, but there is also a part of adaptation that happens in peripheral areas of curve as depicted in Figure 1.2 with surround. Previous psychophysical studies have explored luminance adaptation in foveal view; luminance adaptation at the peak of Gaussian cruve, however, there is lack of research on luminance adaptation in outer regions of foveal view; luminace adaptation in the peripheral areas of Gaussian curve.

2. **[R2]**: Previous psychophyiscal studies on luminance adaptation have explored both luminance contrast and spatial frequency together in unrelated background color as depicted in Figure1.3(a), mostly using Gabor pattern as stimulus. However, there is a lack of research on luminance contrast independent of spatial frequency, especially in related colors.

3. **[R3]**: Oblique effect defines that HVS can perceive better in horizontal and vertical lines than other direction of lines, where as perception between horizontal vs vertical lines is still debatable.

1.4 Contributions

The major contributions of this research are outlined as follows:

- Designed a psychophysical experiment in MATLAB using a modified Landolt C as stimulus to investigate luminance adaptation. Landolt C was used to make the experiment independent of spatial frequency and to mitigate potential response biases among observers as observers were required to accurately identify the direction of gap openings of modified Landolt C, if they find gaps visible. This contribution is in line with the identified research gap **[R2]** mentioned in Section 1.3.
- Conducted a psychophysical study with 30 observers on luminance adaptation in surround regions of foveal view i.e. luminace adaptation in the peripheral areas of Gaussian curve as depicted in Figure 1.2. This contribution addresses the research gap **[R1]** mentioned in Section 1.3.
- Explored luminance adaptation with luminanace contrast independent of spatial frequency in related colors as surrounds depicted in Figure 1.3(b). This contribution addresses the research gap **[R2]** mentioned in Section 1.3.
- Proposed a hypothesis about perception in horizontal and vertical direction, a byproduct contribution of this research, as gap openings of Landolt C were in all four directions, so it can be analyzed from the results that in which direction observers have done more mistakes, and it can be inferred that whether observers had better perception in vertical openings or horizontal. This contribution addresses the research gap **[R3]** mentioned in Section 1.3.
- Open sourced the code of the whole psychophysical experiment written in psychtoolbox MATLAB, available on Github LuminanceAdaptation. Moreover, there is also a simulation code in Github repo, that can be used to investigate the perception of different size of stimulus (Landolt C), gap size of opening of stimulus, width of stimulus, background luminance, surrounding luminance, and surround color. It can be helpful for future studies related to perception of contrast under luminance adaptation.

1.5 Thesis outline

The present dissertation is structured into six primary chapters, with each chapter dedicated to a distinct major component of the thesis. Chapter one provides an introduction to the research, outlining the research questions, the methods employed to address these questions, and the contributions made by this thesis. The second chapter primarily focuses on providing the necessary background knowledge and conducting a literature review to facilitate comprehension of the research conducted in this study. It aims to establish a foundational understanding of the three key pillars of this study, HDR, visual perception, and psychophysics. This chapter further explores the topics related to the pillars employed in this study. Additionally, in chapter three, a more comprehensive examination of the methodology employed in this study is provided. This includes a detailed account of the various stages involved, ranging from the initial conceptualization to the practical execution of the psychophysical experiment. This chapter is further subdivided into three sections. The initial section focuses on the setup of the HDR system, including its creation and verification of functionality. The following section is dedicated to discussing the design and implementation of the experiment, which was developed to address the research questions. The third section pertains to the execution of the experiment, specifically focusing on the methodology employed and the presence of an observer during the experiment. Chapter four focuses on the analysis of data obtained from observers in the psychophysical experiment. The results obtained in this chapter provide insights into how our research questions are addressed. Furthermore, these results are examined with respect to gender and age, aiming to identify potential differences in the outcomes influenced by these factors. Furthermore, last two chapters of this study focuses on the discussion, conclusion, and potential future directions.

2 | Background

If I have seen further, it is by standing upon the shoulders of giants.

Isaac Newton

The human visual system (HVS) is a complex sensory system that has been the subject of ongoing research aimed at comprehensively understanding its intricacies. However, our current understanding of this system remains incomplete, indicating that there is still much progress to be made in this field. This study represents an advancement in our comprehension of the human visual system, specifically in relation to the perception of luminance contrast across varying luminance scales and the mechanisms by which we adapt to these luminance conditions. This study involved the implementation of a psychophysical experiment on a high dynamic range (HDR) display. The subsequent chapter will provide a more comprehensive analysis of high dynamic range imagery, the psychophysical experiment conducted in relation to this study, as well as luminance adaptation and contrast thresholds, with a focus on specifics.

2.1 High dynamic range imagery - HDRI

The word dynamic range has varied meanings depending on the medium where it is being used DiCarlo and Wandell (2000). In case of displays, it is measured by *contrast ratio* that is ratio between luminance of brightest and darkest color a display can produce i.e. white and black Mantiuk et al. (2015). In some displays there is no light emitted at zero level as some HDR displays mentioned in Seetzen et al. (2004) study, then next controllable level after zero will be considered as the darkest color to avoid infinity in contrast ratio definition as shown in the Table 2.1, this ratio is usually normalized such that second value is one, i.e 500:1. In case of HDRI to measure the dynamic ranges of scene, it is measured by *log exposure range* that is difference between the logarithm base 10 of brightest and darkest luminance in the scene, logarithm function describes better the perceived difference of dynamic range than the contrast ratio Mantiuk et al. (2015). A camera's dynamic range is measured by the *signal to noise ratio* (SNR) that is the ratio of the brightness that just saturates the sensor to the luminance that can be observed above the noise level of sensor Mantiuk et al. (2015).

Table 2.1: *Commonly used measures of dynamic range in displays, HDRI processing and cameras. Mantiuk et al. (2015) Myszkowski et al. (2008).*

Name	Formula	Example	Context
Contrast ratio	$\mathrm{CR} = (Y_{\text{peak}} / Y_{\text{noise}}) : 1$	500:1	displays
Log exposure range	$\mathrm{D} = \log_{10}(Y_{\text{peak}}) - \log_{10}(Y_{\text{noise}})$	20.7 order	HDR imaging,
Peak Signal to noise ratio	$\mathrm{PSNR} = 20 \cdot \log_{10}(Y_{\text{peak}} / Y_{\text{noise}})$	53[dB]	digital cameras

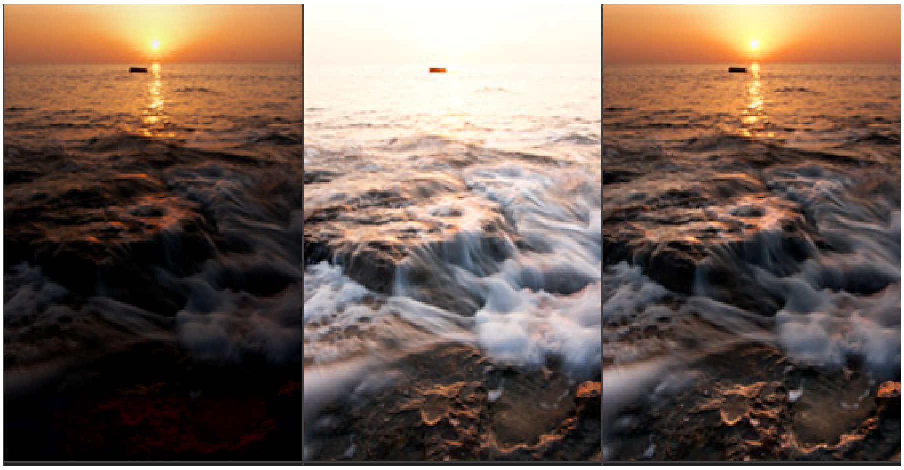


Figure 2.1: *Human visual system perception of an HDR scene. Left image is when eye focuses on background, middle image is when eyes focus on foreground and right image is mental image created in human brain in Colour (2023).*

Human visual system can perceive scenes with higher dynamic range way better than a camera sensor, main reason behind this advantage is neural processing of human brain, human brain creates a mental image (representation of scene in mind) from more than one exposures of natural scene as shown in the figure 2.1. The visual perception of natural scenes, which involves the instantaneous dynamic range of the human eye, is achieved through adjustments in the opening of the pupil. If we only consider the instantaneous dynamic range and assume that the opening of the pupil remains constant, it can be argued that camera sensor systems are superior to human optics systems Lai and Lowrey (2008) Posch et al. (2014) Lee et al. (2018) Atchison (2023). The dynamic range of our eyes is also influenced by the luminance and contrast present in a given scene, a topic that will be explored in subsequent sections.

Representation of real world scenes with high dynamic ranges shown in figure 2.1 as digital images is a hot research topic, and high dynamic range imaging (HDRI) is a way to represent such scenes. High dynamic range images can represent higher levels of colors and luminance than standard dynamic range images, and these “better pixels” Mantiuk et al. (2015) can enhance the overall quality of visual content, that will make it aesthetically more realistic and appealing to the human eye. HDR imagery will be discussed thoroughly further in this section.

2.1.1 Low vs. high dynamic range

In recent years, substantial advancements have been made in the realm of capturing and displaying digital images, resulting in improved quality. However, certain limitations persist in achieving a seamless and highly realistic reproduction of digital images, particularly in relation to constraints on color gamut, luminance, and contrast ranges. These limitations stem from the inherent restrictions imposed by the devices employed for image capture i.e. digital cameras and displaying screens, as well as the formats utilized for image storage. One such limitation arises from the JPEG image encoding method, which utilizes three 8-bit integers within the limited YCrCb color space. As a result, the visible color gamut and the perceived luminance range of this color space as shown in the Figure 2.2, are represented in a restricted manner. Comparable limitations are observed in widely used video standards like MPEG/H.264. Despite the availability of multiple RAW formats with higher precision on modern cameras, it is common practice to convert them to JPEG/MPEG early on, leading to irreversible loss of information. This constraint poses a significant hindrance to the advancement of image processing, storage, and display technologies, limiting their potential for improvement, commonly known as low-dynamic range (LDR) Mantiuk et al. (2015).

Addressing these limitations, high dynamic range imaging (HDRI) offers a solution by incorporating precise pixel color representation, allowing for the accurate depiction of all colors present in the real world and discernible by the human eye. HDRI enables the faithful representation of luminance levels spanning from scotopic to mesopic and photopic vision, thereby accounting for variations in color perception, including the loss of color vision in low-light conditions. For instance, the Hunt’s

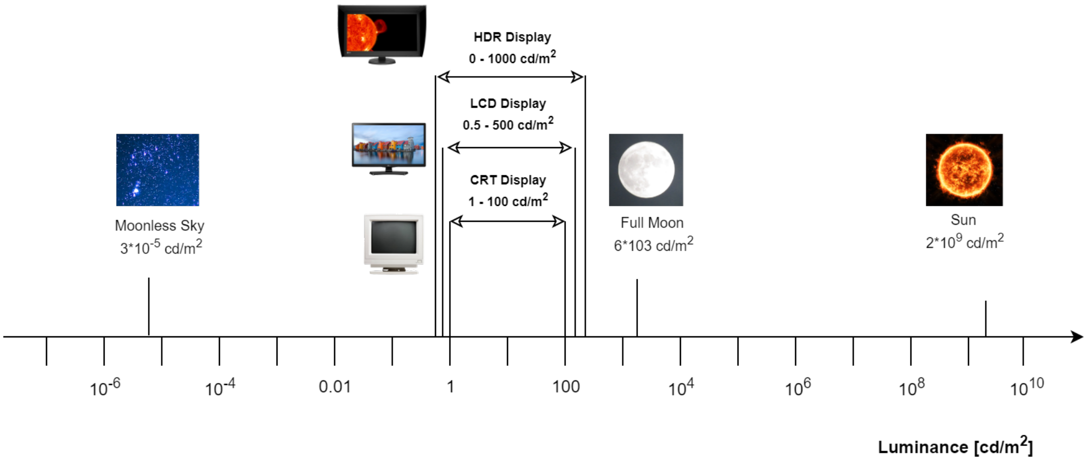


Figure 2.2: *This figure shows the correlation between real-world luminance values and the luminance range that can be exhibited on CRT, LDR, HDR monitors. The majority of digital content is stored in a format that, at maximum, retains the dynamic range commonly observed in standard displays.*

effect, which describes our tendency to perceive objects as more vibrant when well-lit, can be accurately reproduced. To ensure the faithful rendering of enhanced colorfulness, digital images must retain information about the original scene's luminance levels, a feature not achievable with conventional imaging techniques Mantiuk et al. (2015). By overcoming the limitations of LDR, HDRI opens new possibilities for capturing and conveying visual information with greater realism and accuracy.

Nevertheless, digital reproductions continue to struggle with faithfully capturing the true brightness, colorfulness, and contrast exhibited in real-world scenes. These scenes feature heightened contrast levels at both local and global scales, offering crucial perceptual cues. Traditional imaging methods prove inadequate in representing scenes with high contrast and fail to accurately portray phenomena such as self-luminous surfaces, bright specular highlights, visual glare, or the temporary dazzling effect caused by abrupt increases in brightness. To overcome these limitations and achieve accurate reproductions, it becomes imperative to store and process the original scene using high-fidelity HDR techniques. By embracing HDR, the visual fidelity and realism of digital image reproduction can be significantly enhanced, allowing for the faithful capture and portrayal of the intricate details and perceptual characteristics present in real-world scenes Mantiuk et al. (2015).

Another important factor to mention here is the difference between the pixel values of LDR and HDR images. In HDR images, pixels values also called super pixels Mantiuk et al. (2015) are linearly related to luminance which is a photometric measure of the perceived light intensity per surface area independent of the color, where as in practical life these pixel values are never an exact representation of the luminance because of the difference between the spectral sensitivity of cameras used in capturing HDR images and luminous efficiency function of HVS, it has been found out in some studies that there is a 10% deviation of achromatic surfaces from the photometric measurements and 90% deviation in the case of colored surfaces Wüller and Gabele (2007). On the other end, in LDR images, pixel values are not linearly related to the colorimetric or photometric quantity, that is why usage of luminance for the perceived intensity of light in LDR images does not make sense. So, instead of luminance, a term *luma* is used to represent the luminance in LDR images Mantiuk et al. (2015).

2.1.2 Perceivable dynamic range

One important aspect of this study is dynamic range perceived by human visual system which is also a disputed topic itself. Perceived dynamic range by human eye does not have to necessarily correspond to physical range of luminances i.e. contrast ratios or log exposure ranges. One major reason behind this discrepancy of perceived dynamic range and physical range, is the sensitivity of human eye, it is more sensitive in dark lights due to the activation of rods and we perceive changes in smaller steps of luminance levels, such as a change can be perceived between 0 cd/m^2 and 0.1 cd/m^2 but we can not perceive this change at 500 cd/m^2 to 500.1 cd/m^2, our contrast sensitivity is high at lower levels of luminance. A study by Ward (2008) was done to cater this problem and a more relevant and perceptual uniform measure of dynamic range was proposed, *just noticeable contrast differences* (JNDs) offered by a display, it is number of levels a human eye can perceive the differences in the given dynamic range of display.

Another reason of difference between perceivable dynamic range and physical dynamic range is reduction of maximum luminance contrast by to 2-3 log-10 units due to the scattering of light on optics of the eye i.e. lens McCann and Rizzi (2007a) McCann and Rizzi (2007b). However, due to the eye's active nature and its ability to adapt locally and change gaze rapidly, it is believed that people can simultaneously perceive scenes with a dynamic range of 4 or even more log 10 units Reinhard et al. (2010). The effective perceivable dynamic range varies from scene to scene, making it impossible to provide a single definitive number. Nevertheless, studies have shown that people generally prefer images with a dynamic range higher than 100:1 on LDR display, and higher than 1000:1 when presented on a HDR display Yoshida et al. (2006); Daly et al. (2013); Langendijk and Hammer (2010). Thus, it can be confidently stated that we can perceive and appreciate scenes with higher contrast than 1000:1. However, it is important to note that the actual appreciable dynamic range depends on the peak brightness of the scene or display. For instance, while organic light emitting diode (OLED) displays offer high dynamic range, their limited peak brightness restricts most of that range to the low-luminance range, where our ability to distinguish colors is significantly reduced Mantiuk et al. (2015).

2.1.3 Display devices & models

The physical limitations imposed by current display technology make it challenging to realistically simulate real-world appearance. For instance, the ideas of pixels and frames per second are discrete but spatial and temporal information is continuous. However, the human visual system (HVS) also has its own limitations, for instance, the limited density of photo-receptors in the retina and imperfections in eye optics restrict the spatial resolution of perceived details to around 60-70 cycles per visual degree, where as the critical flashing frequency (CFF) in the temporal domain restricts the capacity to distinguish temporal signals over 60Hz Wandell (1995). These limitations are taken into account during the designing of the displays but still a significant lack can be observed with respect to brightness and contrast of HVS.

The advent of HDR displays has reduced the gap between the reproduced brightness and contrast on the displays and perceived brightness and contrast by HVS. There are two basic ways to display the HDR images with higher contrast ratio and brightness.

- Direct precise modulation of each pixel.
- Serial combination of two or more modulators.

The first approach, which involves controlling each pixel with a precision of 12-16 bits, is technologically challenging. It requires the availability of both zero and high luminance values such as 3000 cd/m^2 - 6000 cd/m^2 without any light leaks between neighboring pixels Seetzen et al. (2006). JENOPTIK GmbH's Scanning Laser Display Technology Deter and Biehlig (2004) addresses these requirements by modulating RGB laser beams to create smooth transitions between pixels, resulting in a high contrast ratio exceeding 100,000:1. This technology also offers an expanded color gamut due to the more saturated primaries. However, it is limited by the high cost of the required laser diodes in such technologies Hoefflinger (2007). Organic light emitting diodes (OLED) displays, on the other hand, show promise for HDR applications but face limitations in achieving high luminance levels. So far, no OLED display with a driver capable of 12-16 bit depth has been introduced Mantiuk et al. (2015). Where as, the second approach is more practical for HDR image display, using two modulators that optically multiply independently

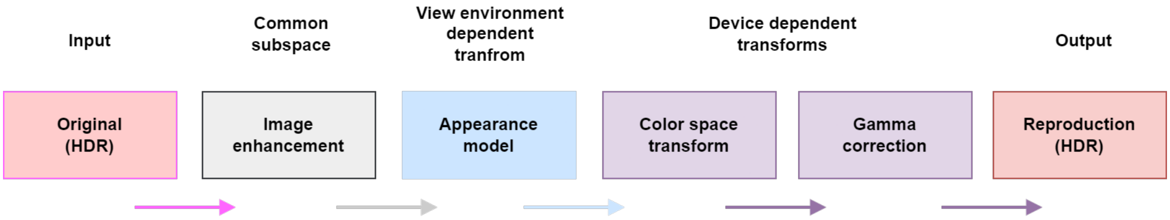


Figure 2.3: *The the processing steps required to present a high dynamic range (HDR) image on a display device with high dynamic range capabilities Reinhard et al. (2008).*

modulated representations of the same image. This method achieves high-quality image contrast with standard 8-bit drivers. The first modulator is a backlight device, such as a grid of light emitting diodes (LEDs), actively emitting controllable light. It illuminates the second modulator, a passive liquid crystal display (LCD) panel or projector, controlling transmitted light on a per-pixel basis. Projectors can utilize LCDs, liquid crystal on silicon (LCoS), or digital micro-mirror devices (DMD) technologies. Low luminance levels are achieved through light attenuation or redirection, though energy efficiency varies. Close to zero luminance is achieved in LED-based backlights, with possible light leakage from neighboring LEDs.

Display models

In color science, display models refer to mathematical or computational models that are used to represent and simulate the behavior of displays Reinhard et al. (2008). These models aim to accurately characterize how colors are displayed on a given device and how they are perceived by viewers taking into account the device limitations and characteristics. Display models take into account various factors that influence color reproduction, including the display's color gamut, gamma correction, color temperature, and viewing conditions. Where as, HDR display models take into account the unique characteristics of HDR displays, such as their extended luminance range, wider color gamut, and specific tone mapping algorithms used to convert HDR content to the capabilities of display. These models aim to accurately predict how colors and brightness levels will be rendered on an HDR display and how they will be perceived by viewers. Different display models and color spaces can be used for HDR, such as the RGB color spaces with higher bit depths (e.g., 10-bit or 12-bit) and wider color gamuts (e.g., Rec. 2020 or DCI-P3). Additionally, specific models and algorithms, such as perceptual quantization or dynamic tone mapping operators, may be employed to optimize the visual experience and maintain the intended appearance of HDR content on different HDR displays Reinhard et al. (2010).

A typical HDR content pipeline on a HDR display is shown in Figure 2.3, where image enhancement step is an optional step that depends on the rendering intent in which some enhancing techniques for pleasantness or accurateness are applied depending on the purpose of displaying the particular HDR content. In next step, an appearance model is applied to account for viewing environment of the display, where as appearance models were developed to account for changes in viewing environment over a relatively small range of luminance values, and color appearance models for larger luminance values is still a debatable topic. Because under normal light conditions HVS is partially adapted by ambient light and partially adapted by display device, under normal circumstances i.e. for SDR displays, adaptation is not a big deal as SDR displays light out is almost same as normal office environment, that is not the case when it comes to HDR displays and it still needs some research how to take into account the partial adaptation Reinhard et al. (2008). In second last step, HDR content is transformed into a device dependent color space using a gamut mapping algorithm according to the primary color values of color gamut and white point used in display. And finally in last step a gamma correction is applied on the linear, enhanced and gamut-mapped input. Gamma correction tries to correct the non-linear relationship between the input voltage and intensity of emitted light of cathode ray tube (CRT), also known as electro-optic conversion curve (EOCF) Poynton (1996). Normally, it is given in a form of a power function $intensity = signal^{\gamma}$, where γ value is normally between 1.8 to 2.8 Mantiuk et al. (2015). But in terms of HDR display, there are two commonly used EOCFs, Perceptual quantization (PQ) and hybrid log-gamma (HLG). PQ provides a better accurate representation of color and light perception with respect to HVS, where as HLG is particularly suited for the live streaming and is compatible with SDR displays.

2.2 Visual perception

The human visual system (HVS) possesses the ability to perceive diverse characteristics of light that enters our ocular organs from the surrounding environment. One fundamental aspect to consider is the concept of intensity, which is closely associated with the power or luminance of light and is subjectively experienced as brightness. Where as, the perception of contrast in our HVS is facilitated by spatial variations in intensity, which in turn enable the differentiation of lines, shapes, and forms. The perception of different colors is generated by variations in intensity throughout the spectrum Murdoch (2013). A thorough comprehension of these concepts can be obtained by referring to Wandell's extensive literature Wandell (1995). Here, only relevant topics to this study are discussed.

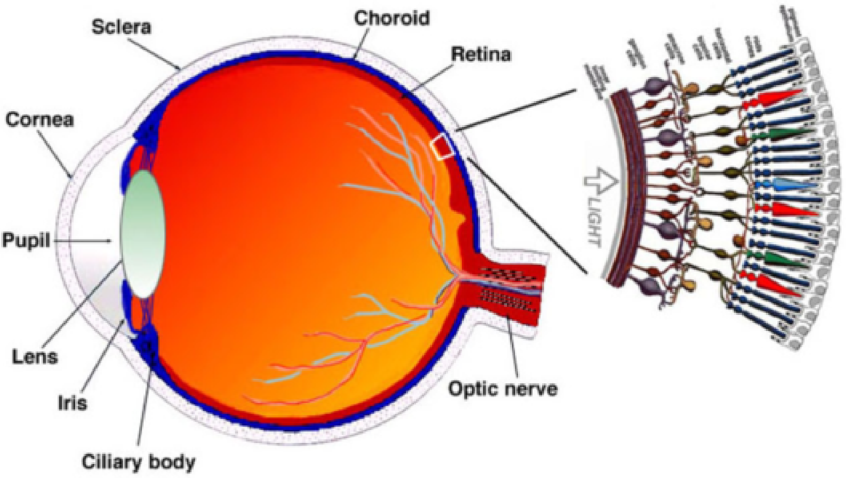


Figure 2.4: *The major components of the human eye are labelled on the left side. In the right side, a detailed examination of the retina reveals the distinct layers of neurons that light traverses prior to reaching the photosensitive rod and cone cells. Murdoch (2013)*

2.2.1 Human ocular organ - Eye

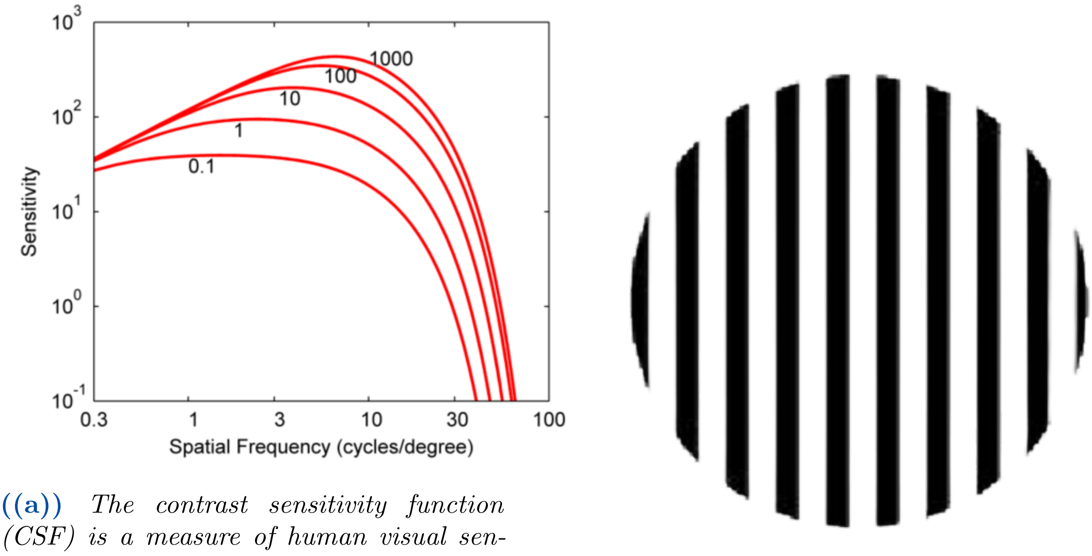
The human visual system (HVS) is a complex mechanism that encompasses the entire process of vision, starting from the reception of visual stimuli by the eyes and ending with the interpretation of these stimuli by the cortical regions of the brain.

The diagram presented in Figure 2.4 depicts the anatomical arrangement of the human eye, which serves as a crucial instrument for the perception of the surrounding environment. The transmission of light occurs as it passes through the cornea, pupil, lens, and the vitreous humour within the eyeball, ultimately reaching the retina. The retina is comprised by a population of photosensitive cells that are used to send signals to visual cortex for further interpretation. These photosensitive cells falls into two basic categories, rods and cones. Rod cells, which exhibit a heightened sensitivity to a wide spectrum of colors and constitute the predominant proportion of retinal cells, estimated to be approximately 10^8 in numbers. Where as, cone cells are further divided in three distinct categories, L, M and S cones, which possess a lower level of sensitivity compared to rods. However, these cone cells play a crucial role in facilitating the discrimination of colors, albeit under conditions of adequate illumination. The number of cones in the retina is estimated to be approximately 5×10^6, with approximately 6% of these cones being sensitive to short-wavelength light (referred to as S cones). The remaining cones are divided between M (middle-wavelength) and L (long-wavelength) cones, with varying ratios observed among different individuals Williams et al. (2003). Cones are primarily localised within the central region of the visual field, specifically in the *fovea*, which is associated with the most acute level of detail perception. In contrast, it is observed that rods exhibit a higher prevalence within the periphery of the retina. It is noteworthy to mention that there exists an additional category of light-sensitive receptors known as melanopsin receptors, which are located within a limited subset of ganglion cells in the retina. Although these receptors are involved in the regulation of the body's circadian rhythm, they are non-visual and fall outside the scope of this thesis.

Another important visual phenomenon to consider is adaptation, which is a significant and complex process that occurs in both the cells of the retina and the visual cortex. Adaptation refers to the ability of our visual system to adjust to changes in the level of lighting we experience. This process is particularly crucial for "night vision", allowing us to see in low-light conditions. However, it also explains why we may experience temporary blindness when transitioning suddenly from darkness to a brightly lit environment. Adaptation ensures that there is no fixed relationship between the physical intensity of light (luminance) and our perception of brightness. Instead, our perception of brightness depends on the surrounding light intensity and recent changes in light intensity that we have experienced. Another related phenomenon is Chromatic adaptation, it is characterised by alterations in the sensitivity of cone cells, as well as modifications in the brain's interpretation of the signals received from these cells. This phenomenon explains the reason why an object, which possesses the ability to reflect all colors and is commonly referred to as a spectrally-white object, exhibits a white appearance irrespective of the prevailing lighting conditions. For instance, the object will retain its white appearance even when exposed to warm, yellow-toned indoor lighting or cool, blue-toned outdoor shading. The perception of color is significantly influenced by the chromatic properties of the surrounding environment and the temporal characteristics of light exposure on the retina. In addition, for a more in-depth exploration and detailed modeling of color appearance, the book "color Appearance Models" by Fairchild Mark (2005) provides a comprehensive and thorough analysis of this complex subject.

2.2.2 Luminance and contrast

Luminance relates to the measured physical intensity of light emitted by an object and subsequently reaching a designated location in space, such as the human eye Murdoch (2013). The measurement is expressed in candela per square metre, enabling a direct and easily measurable assessment. However, understanding the



((a)) *The contrast sensitivity function (CSF) is a measure of human visual sensitivity to spatial frequency at various levels of luminance, expressed in units of candela per square metre (cd/m2). Murdoch (2013)*

((b)) *Gabor pattern or sine wave grating with regular spacing commonly used in visual perception experiments.*

Figure 2.5: *The contrast sensitivity function (CSF) was derived from empirical data sets primarily utilising gabor patterns. Analysis of the left figure reveals that as the luminance of the stimulus increases, sensitivity also increases and reaches its peak at higher frequencies. However, it is worth noting that the maximum discernible frequency is approximately 50 cycles per degree.*

perception of luminance is a more intricate matter because of an array of factors, that include temporal and spatial influences, alongside adaptation mechanisms within the human visual system (HVS). It is notable that visual perception predominantly depends on disparities in luminance, commonly referred to as contrast as discussed in Peter Barten's book Barten (1999).

To understand the spatial and temporal characteristic of HVS, fourier theorem is used. It states that,

> *It is possible to express any signal or image with spatial variation in luminance as a linear combination of sine waves. By establishing the system's response to various luminance fluctuations in sine-wave gratings, it becomes possible to anticipate the system's performance when presented with any image Kelly (1977).*

In the case of controlled and periodic variations in luminance, such as sine waves demonstrating spatially varying brightness shown in Figure 2.5(b) also known as gabor pattern, it is possible to better understand the sensitivity of our visual system by taking into account certain factors. These factors include the average luminance, the amplitude of the sine wave modulation, and the spatial frequency measured in degrees of visual angle. A combination of these factors, along with signal-to-noise principles, provides a theoretical framework for explaining the functioning of our visual system Barten (1992). A sine wave grating pattern as stimuli shown in Figure 2.5(b) is commonly used pattern in psychophysical based experiments to understand the human visual system as it has been proved through studies that HVS is more sensitive towards the regular spacing contrasts than others Campbell and Maffei (1974) Pollen and Ronner (1983). The contrast sensitivity function (CSF), as depicted in Figure 2.5(a), offers a comprehensive representation of our perceptual ability in detecting contrast. It denotes the reciprocal of the minimum noticeable changes in luminance as explained in study of Barten Barten (2003). The contrast sensitivity function (CSF), which has been established through multiple studies on contrast sensitivity, demonstrates a robust correlation with the spatial frequency of luminance variations. It exhibits maximum sensitivity within the range of 3 to 10 cycles per degree, and experiences a substantial decline at approximately 50 cycles per degree.

In the domain of vision research, luminance contrast is commonly characterised as

$$C = \frac{\Delta L}{L} \tag{2.1}$$

where variable ΔL is used to represent the amplitude of the sine wave grating or any other contrast stimulus, whereas L is used to denote the background luminance. The concept of contrast, as defined by experimental psychological studies, has been employed for over a century Mantiuk et al. (2015). These studies have revealed that the smallest perceivable difference in luminance, denoted as ΔL, on a uniform background is directly proportional to the luminance of the background, denoted as L. Furthermore, this relationship remains relatively constant, that is represented as,

$$\frac{\Delta L}{L} = k \tag{2.2}$$

where k is Weber fraction and this relation is known as Weber law after the name of a German psychologist Ernst Heinrich Weber. But recently this Weber law has been revised as it was found that Weber fraction k changes with background luminance, spatial frequency of the signal and several other parameters Mantiuk et al. (2015). One simple modification to Weber law that has worked better than Weber law itself, is to allow the constant k change with background luminance based on contrast sensitivity models Mantiuk et al. (2005) Mantiuk et al. (2004).

2.3 Pyschophysical study

Psychophysics is an academic discipline that investigates the correlations between objective measurements of physical stimuli and the subjective sensations and perceptions that are provoked by those stimuli Fairchild (2013). Psychophysics is a scientific discipline that can be regarded as similar to conventional disciplines like physics, chemistry, and biology.

Psychophysics employs various methodologies to obtain objective and quantitative measurements of perceptual phenomena, which are typically regarded as subjective in nature. It is crucial to acknowledge that the outcomes of appropriately constructed psychophysical experiments possess the same level of objectivity and quantifiability as the act of measuring length using a ruler or any other physical measurement tool. One notable distinction lies in the fact that the uncertainties related to psychophysical measurements often exhibit a considerably greater magnitude compared to the uncertainties observed in most physical measurements. Nevertheless, the outcomes remain valuable and significant, provided that these uncertainties are taken into account, as is customary for physical measurements. Psychophysics is a scientific discipline employed to investigate various aspects of human perception, and occasionally, animal perception. The focus of this study pertains to visual perception of humans, with particular emphasis on the field of visual psychophysics.

Visual experiments further falls into two categories:

1. Threshold and matching experiments, designed to assess visual sensitivity towards subtle variations in stimuli, also known as perceptual equality.

2. Scaling experiments, intended to establish a correlation between the physical attributes and the perceptual dimensions of stimuli.

It is of paramount significance to initially ascertain the suitable class of experiment for a given application. Threshold experiments are a suitable method for quantifying the degree of sensitivity to alterations and the ability to perceive stimuli. In contrast, scaling experiments are deemed suitable in situations where it becomes essential to establish the associations between stimuli. This study employed a threshold and matching experiment to investigate the luminance thresholds of the human visual system, specifically focusing on the point at which certain contrasts become imperceptible. Furthermore, this section makes references to analogous studies that not only correspond with the present research but also served as its basis.

2.3.1 Related psychophysical studies

The human visual system exhibits a notable capacity to adapt to scenes characterised by a wide range of luminance levels by integrating multiple exposures of these scenes. Considerable research has been undertaken to comprehend this phenomenon, and numerous approaches have been proposed to replicate this adaptive mechanism. In the year 2000, Pattanaik et al. (2000) proposed the introduction of a new operator that replicates the functioning of the human visual system (HVS). This operator considers the temporal information, as the HVS requires time to adjust to significant variations in scene intensity. The purpose of this operator was to evaluate the visual reaction of individuals towards animations and interactive real-time simulators, in relation to real-world environments. Nevertheless, the main objective of this operator was to attain a high level of speed and real-time applicability, which required computational efficiency and simplicity. Ledda et al. (2004) presented an extension of prior research, proposing a model for local adaptation, this model is dependent on physiological data and provides a smooth integration with pre-existing rendering software. The implementation of the function can be approached in two ways: as a static function for processing individual images, or as a method for temporal adaptation in a sequence of images. In the latter case, various factors need to be taken into consideration, including the duration of time that has elapsed and the intensity of preadaptation, particularly in the context of a dynamic sequence. Moreover, the effectiveness of this methodology was additionally validated through a psychophysical study carried out using a high dynamic range (HDR) display.

The investigation of display aesthetics has also been a prominent area of study since the introduction of display systems. Numerous factors contribute to these aesthetics, with color science playing a significant role. Key factors pertaining to color science include color gamut, resolution, dynamic range, contrast, and luminance. In the year 2010, a set of psychophysical experiments were undertaken by Kunkel and Reinhard (2010) with the aim of comprehending the simultaneous dynamic range of the human visual system (HVS) on a high dynamic range (HDR) screen, while being fully adapted to a specific background luminance. The study revealed that the human visual system (HVS) possesses the ability to distinguish a contrast threshold over a range of 3.7 log units of luminance under specific variable conditions. Additionally, the study examined the impact of stimulus duration, stimulus contrast, and background illumination on the dynamic range of the HVS. In 2011, a study conducted by Matsumoto et al. (2011) aimed to determine the optimal luminance levels for LCD TV screens in typical household viewing conditions, with the objective of enhancing screen visibility while minimizing power consumption. Various experiments were conducted to determine the preferred viewing angles of typical individuals in household settings. Additionally, subjects were instructed to adjust the luminance level based on their personal comfort, and the impact of screen illuminance on TV appearance was investigated. This study was conducted with the participation of 83 households in order to determine the optimal viewing angle commonly employed in their daily routines. A psychophysical experiment was conducted on two groups comprising 24 young subjects, with an average age of 22, and 24 elder subjects, with an average age of 71. The study findings indicate that, under specific conditions, a luminance of 160 cd/m^2 was found to be preferred by younger subjects, while older subjects preferred a luminance of 248 cd/m^2. These results suggest that energy consumption can potentially be reduced by applying the insights gained from this research.

In 2012, another study was conducted by Lee et al. (2012) to identify the optimal luminance level for assessing the emotional image quality of a display, taking into consideration the display's loading ratio and the maximum luminance that does not induce glare or visual fatigue in the human eye. Glare is characterised as the sensation of discomfort or ocular distress resulting from exposure to intense illumination. Two psychophysical experiments were conducted utilising an Organic Light-Emitting Diode (OLED) display and a Liquid Crystal Display (LCD) display. The initial experiment involved the determination of appropriate luminance levels based on the content depicted in the images. The second experiment aimed to determine the maximum luminance level that does not induce glare in human eyes. In the conducted experiments, participants were instructed to choose visually appealing images based on a reference image displayed on a screen under specific luminance conditions. The results indicated that participants deemed a luminance level of 150 cd/m^2 to be suitable for the full luminance of the display; whole display is emitting same luminance with 100% area. Additionally, for the peak luminance (the highest luminance) on the display, participants expressed a preference for it to fall within the range of 400-450 cd/m^2. This study represents a pioneering effort in establishing a degree-based circular field of view for assessing the glare threshold of human eyes in both dark environments (0 lux) and environments with ambient light (150 lux). It has been determined that human visual perception is more adept at detecting glare in conditions of lower luminance, such as dark environments, compared to well-lit environments. It has also been established that the threshold for experiencing glare is contingent upon the field of view. Specifically, as the field of view expands, individuals are more likely to encounter glare. However, it has been determined that users can encounter glare within the range of 300-600 cd/m^2. In 2016, a similar study by Fang et al. (2016) was undertaken to investigate the appropriate luminance levels for HDR TV systems in order to mitigate discomfort glare. This study, conducted in 2016, employed psychophysical experiments as its methodology. The mentioned study utilised a 47-inch LCD display equipped with LED backlight technology, boasting a maximum luminance of 1800 cd/m^2 and a correlated color temperature (CCT) of 1200K. The primary objective of this investigation was to ascertain the luminance threshold associated with the perception of glares. The rationale for employing LCD technology instead of OLED technology lies in the former's independence from average picture level (APL), which enables it to yield superior outcomes in psychophysical experiments. The psychophysical experiment was conducted in accordance with the criteria set forth by the Illuminating Engineering Society of North America (IES), utilising a sample size of 24 observers. The observers were required to determine the glare threshold in relation to the average picture level (APL) for two distinct correlated color temperatures (CCTs), namely 1200K and 6500K. This assessment was conducted under two distinct lighting conditions: a dark room and an ambient light setting with an illuminance of 200lx. Empirical evidence has indicated that a luminance level of 600 cd/m^2 is considered optimal for High Dynamic Range (HDR) television systems. Furthermore, a recent study conducted in 2022 by Liu et al. (2022) aimed to forecast visual comfort for mobile displays. A psychophysical experiment was conducted to examine the effects of luminance and illuminance levels on three different mobile displays. The luminance levels tested were 100, 250, and 500 cd/m^2, while the illuminance levels tested were 0, 10, 100, 500, and 1000 lx. The experiment was conducted with the assistance of 60 observers, who were divided into three distinct age groups, each consisting of an equal number of subjects (n=20). Participants were instructed to provide their responses utilising a six-category rating scale across 42 different combinations of text backgrounds. The study revealed that visual comfort is significantly influenced by the contrast in lightness, particularly among individuals of different age groups. Specifically, for elderly observers, visual comfort tends to increase as the difference in lightness between the luminance of the text and the luminance of the background increases.

A study was conducted in 2016 by Sun et al. (2017) to examine the impact of various factors, including stimulus luminance, surround luminance, background luminance, background orientation, and background size, on color perception in non-uniform surround conditions. This investigation employed two psychophysical experiments. The experimental findings indicate that color perception is significantly affected by the size of the background and the luminance of the surrounding area, while the orientation of the background has minimal impact. Furthermore, two models were additionally proposed in this study. The first model aims to determine optimal parameters for the CIECAM02 color appearance model in lighting applications. The second model is a CIE Uniform Glare Rating (UGR) based model that has been optimised specifically for brightness estimation. This study additionally incorporated the utilisation of a Gaussian-like functions to estimate the luminance of the adapting field.

In recent times, there has been a significant amount of research conducted on color appearance models and their enhancement. A study conducted in 2022 by Phung et al. (2022) examined the perception of brightness appearance in self-luminous stimuli against non-uniform backgrounds. This research was motivated by the observation that existing computational models, such as CAM models, primarily focus on stimuli perceived under uniform backgrounds. A psychophysical experiment was designed wherein a neutral ring-shaped luminous region was incorporated into the backdrop of a neutral circular stimulus. The ring was exhibited at three different levels of luminance, specifically 90, 335, and 1200 cd/m^2. Additionally, it was presented at three varying thickness levels, 0.33, 0.67, and 1.00 cm. These presentations were made at angular distances from the edge of the stimulus, which were measured to be 1.2°, 6.4°, 11.3°, and 16.1°. The study revealed that a decrease in the distance between the stimulus and the ring resulted in a greater magnitude of brightness inhibition. This phenomenon was also found to be associated with the area of the rings and their luminance levels. It has been observed that the existing CAM models are inadequate in addressing such semi-saturated situations, and it was recommended that, future CAM models should incorporate measures to mitigate this limitation.

3 | Methodology

> *Research is to see what everybody else has seen, and to think what nobody else has thought.*
>
> **Albert Szent-Györgyi**

The present study utilized Psychotoolbox MATLAB Psy (2023) to conduct a psychophysical experiment aimed at determining the luminance thresholds of contrast perceived by HVS on an HDR display. This section provides detailed information regarding the experimental setup, including any challenges faced during the process and the corresponding resolutions that were implemented.

3.1 HDR setup

To establish an HDR setup, specific hardware is required to execute the HDR pipeline, which, in this particular experiment, involved a 10-bit pipeline. All components involved in such pipelines must be compatible to HDR, including the display monitor, the graphics processing unit (GPU), and the cables connecting the monitor and GPU. The process of determining the HDR compatibility of each individual component can be a laborious and time intensive process. To determine if a display monitor supports HDR imagery, one can consult the display manual. Similarly, information regarding the compatibility of the GPU with HDR 10-bit pipeline can be obtained from the manufacturer's guide, typically available on their website. However, the task of determining the suitable cable for HDR support may present greater difficulty. Although a display port is typically recommended for the HDR pipeline EIZ (2023), it was discovered that the display port used in this

Figure 3.1: *High dynamic range display EIZO Prominence CG3146 used in this study with a colorimeter embedded at the top of the display.*

setup did not support HDR, leading to some further investigation. Eventually, it was found that the HDMI cable supported the HDR 10-bit pipeline. The following section discusses in detail the devices utilized, their usage, and the steps taken to establish the HDR setup employed in the experiment.

3.1.1 Display monitor

To display an HDR image, typical display monitors are not sufficient, so HDR enabled display monitors are used, that has capability to show more colors; to have a color gamut that supports more colors, and can go up to luminance 1000 nits. In this experiment an HDR display monitor, EIZO Prominence CG3146 as shown in Figure 3.1 has been used.

The Eizo ColorEdge CG3146 is a high-quality professional monitor specifically designed for use in 4K post-production, studio environments, and 4K cinematography. This monitor offers support for both perceptual quantization (PQ) and hybrid log-gamma (HLG) curves, which are essential for displaying HDR content EIZ (2023). PQ provides a more accurate representation of color and light perception with respect to the HVS, while HLG is particularly well-suited for live streaming and is compatible with SDR displays. Both electro-optical transfer functions (EOTF) have been standardized by the International Telecommunication Union (ITU) as ITU-R BT.2100. Additionally, the PQ curve has been standardized by the Society of Motion Picture and Television Engineers (SMPTE) as ST-2048, ensuring consistency and compatibility across different systems and devices. The monitor also comes with a built-in calibration sensor that ensures the image shown on the display is more accurate and realistic.

Moreover, It is mentioned on the Eizo display website EIZ (2023) that, this display covers 99% of the DCI-P3 color space and has a 3D LUT which adjusts colors individually on an RGB cubic table. It features a 31.1-inch IPS panel with a resolution of 4096 x 2160 pixels and a brightness of up to 1000 cd/m^2. It also has a contrast ratio of 1,000,000:1 to display true blacks. In addition to its impressive features, this display incorporates an AI algorithm that intelligently senses and estimates the surrounding environment and monitor temperature. This algorithm adjusts graduations, color, brightness, and other characteristics to ensure accurate and precise display representation, compensating for any shifts that may occur due to changes in ambient conditions and the monitor's temperature. What sets this display apart is its quick stabilization time, as it achieves a reliable and stable color display within just three minutes of being turned on, a significant improvement compared to the typical 30-minute stabilization period required by conventional monitors to stabilize brightness, chromaticity, and tone characteristics.

3.1.2 Graphic processing unit

After the display monitor, the next crucial component in a 10-bit HDR pipeline is a GPU that supports HDR. In general, GPU manufacturers provide information on their official websites regarding the compatibility of their GPUs with HDR technology. In this experiment, a Quadro RTX 5000 GPU from Nvidia was initially used for the HDR pipeline, along with a display port cable version 1.4. However, the Windows 11 HDR option was not available, despite the GPU's claimed HDR support on the manufacturer's website. Subsequently, an HDMI cable was used instead of display port; however, as the GPU lacked the HDMI port, a converter from HDMI to display port was used. Consequently, the Windows 11 HDR option became accessible. Nevertheless, calibration of the monitor remained problematic and determined reason of this problematic behavior was employed converter. To address the issue, the GPU was replaced with an Nvidia Titan X, which was equipped with an HDMI port. The introduction of the new GPU facilitated the integration of HDR support into Windows 11, and additionally, the calibration process was executed seamlessly. It is crucial to acknowledge that the cable that establishes a connection between the GPU and the display monitor holds significant importance within the HDR pipeline.

To enable the GPU to work for a 10-bit pipeline, several essential steps need to be taken. By default, the GPU supports an 8-bit pipeline, but this can be adjusted in the Nvidia control panel. The table below outlines the properties that were changed and the corresponding values.

In this configuration, the color depth i.e. bits per color channel (bpc) are set to 10, allowing for more precise representation of colors. The output color format

Table 3.1: *Table to show the essential setting used for the Nvidia GPU for HDR pipeline.*

Nvidia GPU Settings	
Property	Value
Resolution	4096 * 2160
Refresh Rate	50 Hz
color depth	10 bpc
color format	YCbCr422
Dynamic range	Limited

is configured as YCbCr422, which indicates the utilization of the YCbCr color space with 4:2:2 chroma subsampling. This compression technique allows for the transmission of the full luminance signal, while only transmitting half of the color signal. Fortunately, this compression method does not impact the experiment, as the stimuli employed in experiment are achromatic. Additionally, the dynamic range is set to limited, meaning that typical colors do not utilize the extreme values of the 10-bit system. Instead, these extreme values are reserved for highlighting and dark features. For instance, in an 8-bit system, the range of 16-235 is typically used for normal colors, while the remaining values are allocated for highlights and dark colors. By modifying these settings in the Nvidia control panel, the GPU can be configured to support a 10-bit pipeline, enabling accurate and high-quality color reproduction.

3.1.3 Sanity check of HDR pipeline

Ensuring the functionality of the HDR pipeline is one of the major challenges while working in a HDR setup Vibhoothi et al. (2023). To overcome this hurdle, several methods were employed. Firstly, guidelines provided on DisplayHDR website referenced as DisplayHDR (2023) were followed to ensure the correct setup of the HDR pipeline. Once the setup was completed according to the guidelines, the Psychotoolbox HDR Matlab demo codes were utilized. These demo codes serve as a reliable indicator of HDR support in the pipeline, as they should run smoothly without any errors if the pipeline is properly functioning. It is important to note that the installation of Psychotoolbox on Matlab is required, along with the installation of pre-requisite libraries. Once Psychotoolbox is installed, the SimpleHDRDemo.m script within Psychotoolbox was executed to verify if it could successfully preview an HDR image as shown in Figure 3.2. This process helped assess the functionality of the HDR pipeline and ensured its proper operation.

Additionally, a MATLAB code was implemented in Psychtoolbox to display

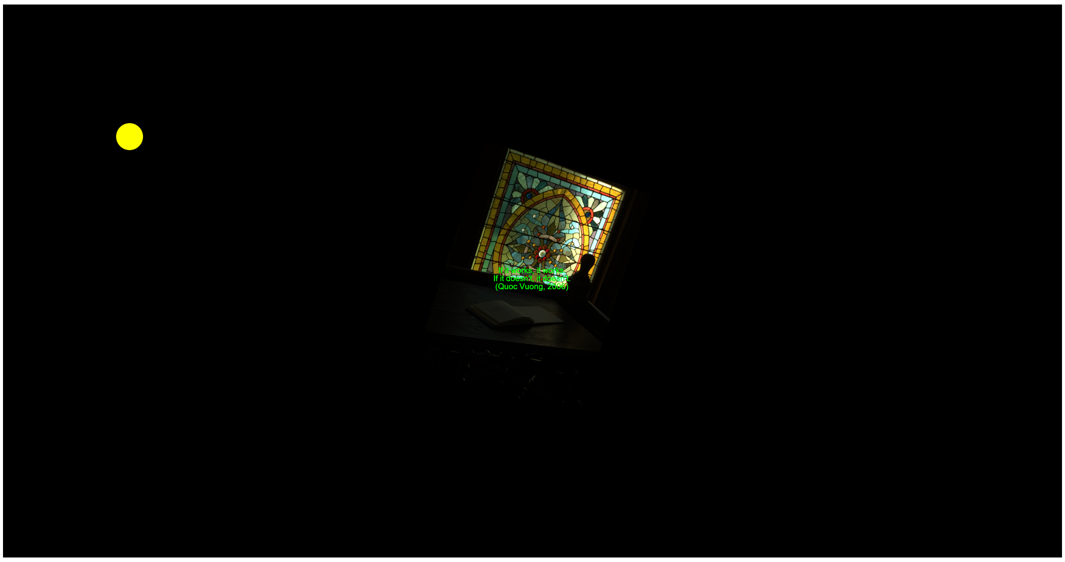
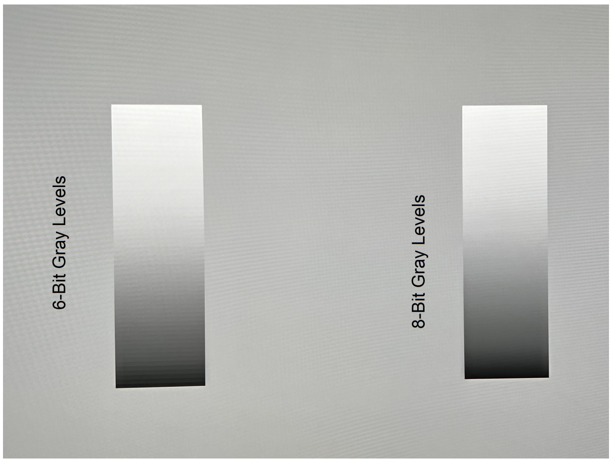


Figure 3.2: *High Dynamic Range image displayed on HDR Eizo screen using SimpleHDRDemo.m psychtoolbox code. This script was run without any input to ensure the successful installation of psychtoolbox and HDR pipeline.*

gray level gradients in both 8 bits and 10 bits. The objective was to observe the smoothness of transitions in the gray levels of the 10-bit image, as depicted in Figure 3.3(b). In both gradients, the width of each level was fixed, with the 8-bit gradient having 255 steps (accommodating 256 unique values) and the 10-bit gradient offering 1023 steps (allowing for 1024 unique values). Although Figure 3.3(b) does not showcase an actual 10-bit image as a 10-bit image can only be displayed on a 10 bit enabled system with supporting softwares and pdf does not support 10 bit system yet. Furthermore, it illustrates that the gray level transitions in the 10-bit gradients exhibit greater smoothness in comparison to the 8-bit gradients. Nevertheless, the increased level of smoothness exhibited by the 10-bit gray scale is more perceptible when viewed on a HDR display.

Furthermore, a comprehensive evaluation was conducted to assess the luminance emitted by the display across various bit depths. This final test involved displaying white patches with maximum values corresponding to 8-bit, 9-bit, 10-bit, 11-bit, and 12-bit representations. Specifically, the white patch for 8-bit had a value of 255, the 9-bit patch had a value of 511, the 10-bit patch had a value of 1023, and so on. These patches were presented on the HDR display using the Psychtoolbox HDR functionality, and the luminance emitted by each patch was measured using a spectroradiometer Konica Minolta CS-2000. The results of this test, as illustrated in Figure 3.4(a) and summarized in Table 3.4(b), provided valuable insights into the HDR display's performance and its ability to accurately represent and emit

((a)) *High Dynamic Range image generated with 8-bit gray level and 10-bit gray level gradients, displayed on HDR Eizo screen using psychtoolbox in Matlab. The presented levels illustrate the degree of transition smoothing in both 8-bit and 10-bit systems. It is expected that the 10-bit system would exhibit a higher level of smoothness compared to the 8-bit system when viewed on a HDR screen.*



((b)) *Simulation: The purpose of this simulation is to illustrate the expected outcome in terms of gray level gradients for both 8-bit and 10-bit representation on an HDR display. Upon close examination to this figure, it becomes apparent that 8-bit gray levels exhibit a greater degree of smoothness compared to 6-bit gray levels. The ability to discern transitions or steps within the gray levels is notably more challenging in the case of 8-bit as opposed to 6-bit. Similar outcomes can be anticipated when presenting 10-bit and 8-bit grayscale levels on a HDR display.*

light across different bit depths.

By conducting these tests and analyzing the results, it becomes possible to assess the functionality and performance of the HDR pipeline. The guidelines provided by DisplayHDR were followed to ensure the correct setup of the pipeline, and the Psychotoolbox HDR Matlab demo codes were used to verify its proper operation. The comparison of gray level gradients in 8 bits and 10 bits demonstrated the smoother transitions in the 10-bit gradients, indicating the benefits of higher bit depths for achieving smoother gray levels. Furthermore, the measurement of luminance for different bit depths provided insights into the HDR display's performance in terms of emitted light. Overall, these methods and tests contribute

((a)) *Luminance capturing setup of white patches using Konica Minolta CS-2000.*

Nvidia GPU Settings	
Bit System	Luminance
8-bit (255)	253.69 cd/m^2
9-bit (511)	507.93 cd/m^2
10-bit (1023)	998.56 cd/m^2
11-bit (2047)	998.66 cd/m^2
12-bit (4095)	998.46 cd/m^2

((b)) *Table represents luminance values reached by HDR screen emitted by a white patch in different bits system and captured by a Konica Minolta CS-2000.*

Figure 3.4: *Luminance estimation of maximum values of different bit systems in HDR pipeline.*

to ensuring the functionality and optimal operation of the HDR pipeline.

3.1.4 Calibration

Display calibration in the context of HDR refers to the process of adjusting the settings and characteristics of an HDR display to accurately reproduce the extended dynamic range, wider color gamut, and other visual elements specific to HDR content. The goal is to ensure that the HDR display faithfully represents the intended HDR content with accurate colors, contrast, and highlights and shadows.

Here are some key aspects of display calibration in HDR:

- Extended Dynamic Range: HDR displays are capable of reproducing a wider range of luminance levels, from deep blacks to bright highlights. Display calibration in HDR involves adjusting the display's settings, such as peak brightness, black level, and gamma, to accurately represent the full range of luminance in HDR content. This helps preserve details in both the darkest and brightest parts of the image.

- Wide color Gamut: HDR content often utilizes a wider color gamut, such as DCI-P3 or BT 20202(Rec. 2020), which can reproduce a larger range of colors compared to standard displays. Display calibration ensures that the HDR display accurately reproduces these expanded color spaces, maintaining color accuracy and fidelity in HDR content.

- Tone Mapping: Since HDR content typically has a higher dynamic range than what can be fully displayed on most HDR displays, tone mapping techniques are employed to map the HDR content to the display's capabilities. Display calibration involves adjusting the tone mapping parameters to achieve an optimal balance between preserving details, contrast, and overall image quality.

- Highlight and Shadow Details: Display calibration in HDR ensures that the display accurately reproduces the details in both highlights and shadows. This involves adjusting the display's settings to prevent clipping of highlight and shadow information and to maintain a smooth transition between different luminance levels.
- Accuracy and Consistency: Calibration helps ensure accurate and consistent HDR performance across different HDR displays by creating ICC profiles. This is particularly important for professional workflows where accurate color grading, video editing, or visual effects work is required.

To calibrate an HDR display, specialized calibration tools and software solutions are used. These tools measure and adjust various display settings, including luminance, color accuracy, and tone mapping parameters, to achieve accurate and consistent HDR representation. The calibration process is done mostly using a colorimeter, spectrophotometer, or other hardware devices to measure the display's performance and generate calibration profiles or metadata. In this study, a built-in display colorimeter, x-rite i1 display pro colorimeter and Konica Minolta CS-2000 were used to calibrate the HDR display with the help of ColorNavigator 7 EIZO Corporation (2019) and i1Profiler X-Rite (2023) as discussed further below.

3.1.4.1 Colorimeter

A colorimeter is a device utilized for measuring and analyzing color in various industries, including photography, graphic design, printing, and display calibration. This device is designed to precisely quantify the color characteristics of objects or displays. In the case of the EIZO display, the calibration process was performed using the built-in colorimeter sensor of the display itself. This calibration was achieved using the ColorNavigator 7 software, which facilitated the adjustment of various properties to ensure accurate color representation. The specific settings used during the calibration process are detailed in Table 3.2, and the calibration procedure is visually illustrated in the Figure 3.5.

3.1.4.2 X-Rite i1 display pro

The X-Rite i1 Display Pro XRite (2023) is a popular colorimeter and spectrophotometer device used for display calibration and profiling. It is designed to ensure

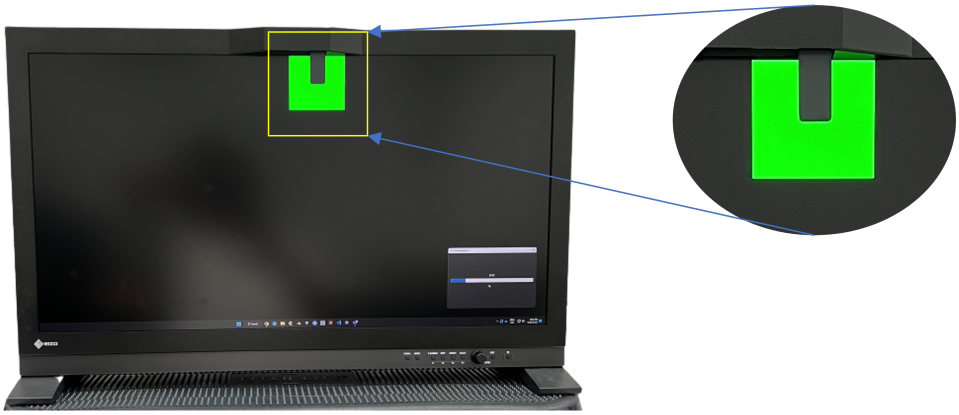


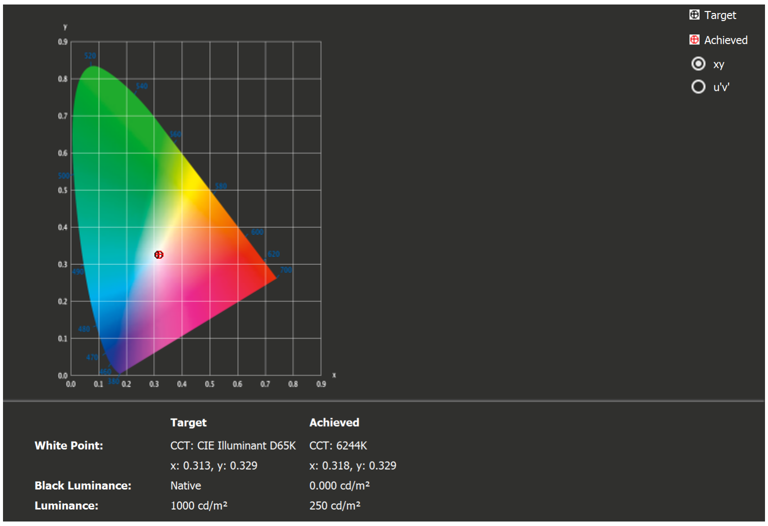
Figure 3.5: *Built-in colorimeter of ColorEdge EIZO Prominence CG3146 used for calibration.*

accurate color reproduction on computer monitors, projectors, and other display devices. EIZO display was also calibrated with a x-rite i1 display pro as shown in Figure 3.6 with the help of a software i1Profiler X-Rite (2023) as ColorNavigator 7 does not support the x-rite i1 display pro anymore. Moreover, to calibrate the display following properties as shown in the table 3.2 below were used but it was found that x-rite i1 display does not calibrate the monitor above 250 cd/m^2 as it is shown in Figure 3.7 that was captured while calibration of display with x-rite i1 display pro, hence this device could not be used for calibration in the study further.

Figure 3.6: *Calibration with x-rite i1 display pro of EIZO Prominence CG3146 display.*

3.1.4.3 Konica minolta spectroradiometer CS-2000A

The Konica Minolta Spectroradiometer CS-2000A Konica Minolta (2023) is a highly advanced and precise instrument used for measuring and analyzing light and color. It is primarily utilized in industries such as display manufacturing, lighting design, and quality control. Eizo display was also calibrated with Konica Minolta using colornavigator 7 software with setting as shown in Table 3.2, and calibration process is visually illustrated in the Figure 3.4(a),



	Target	Achieved
White Point:	CCT: CIE Illuminant D65K x: 0.313, y: 0.329	CCT: 6244K x: 0.318, y: 0.329
Black Luminance:	Native	0.000 cd/m²
Luminance:	1000 cd/m²	250 cd/m²

Figure 3.7: *Calibration with x-rite i1 display pro of EIZO Prominence CG3146 display can not go above than 250* cd/m^2 *as it is shown in luminance above that target was 1000* cd/m^2 *but only 250* cd/m^2 *was achieved after calibration.*

Display calibration in HDR is important to ensure that the HDR content is accurately represented, preserving the artistic intent and providing an immersive viewing experience with vibrant colors, high contrast, and detailed highlights and shadows. There can be different ways to measure the accuracy between different calibration devices but one of them is assessed by evaluating the color difference, measured using the ΔE2000 metric. Table 3.3 demonstrates that the Konica Minolta CS-2000 calibration device outperformed other devices, exhibiting lower ΔE2000 values. As a result, the Konica Minolta CS-2000 was selected as the calibration device for the experiment, ensuring precise and reliable calibration of the display.

Table 3.2: *Table to show the essential setting used for the calibration of HDR screen using different devices.*

Calibration Settings			
Property	Target	Result-Colorimeter	Results-CS-2000
Brightness	1000 $\mathrm{cd\,m^{-2}}$	999.9 $\mathrm{cd\,m^{-2}}$	999.4 $\mathrm{cd\,m^{-2}}$
Black level	Minimum		
White point	D65	x:0.3126 y:0.3290 6509 K	x:0.3127 y:0.3290 6507 K
Gamma(EOTF)	PQ		
PQ Option	1000 $\mathrm{cd\,m^{-2}}$ Clipping		
Gamut	BT.2020		
R	x:0.7080 y:0.2920	x:0.6833 y:0.3134	x:0.6864 y:0.3110
G	x:0.1700 y:0.7970	x:0.2143 y:0.7249	x:0.2169 y:0.7235
B	x:0.1310 y:0.0460	x:0.1489 y:0.0546	x:0.1498 y:0.0546

Table 3.3: *Table to show the $\Delta E2000$ error details of all the calibration devices in different colors.*

Calibration Results			
Name	Values	ΔE2000 Coloritmeter	ΔE2000 CS-2000
Black	0 0 0	0.00	0.00
Blue	0 0 1023	47.82	47.58
Green	0 1023 0	51.09	50.60
Red	1023 0 0	52.19	51.65
Cyan	0 1023 1023	51.31	50.60
Magenta	1023 0 1023	51.30	50.92
Yellow	1023 1023 0	51.44	51.41
Gray-1	128 128 128	0.01	0.02
Gray-2	385 385 385	0.08	0.15
Gray-3	642 642 642	0.13	0.19
White	1023 1023 1023	48.47	48.47

3.2 Experiment

The ideation and building of the psychophysical experiment involved a systematic and iterative approach to address the research questions effectively. Various combinations and setups were explored to optimize the experimental design. To facilitate a better understanding of the experiment and its visual representation, a simulation was developed using Psychtoolbox of Matlab. This simulation allowed for the assessment of how the experiment would appear on an HDR screen, providing valuable insights into the perceptual experience for participants.

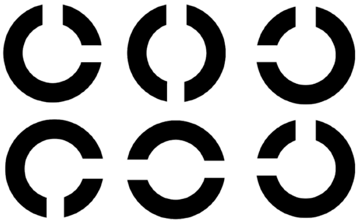
For more comprehensive information and access to the Matlab simulation, you can refer to the GitHub repository at LuminanceAdaptation. The simulation serves as a valuable resource for researchers and participants to gain a deeper understanding of the experimental setup and the expected visual outcomes.

3.2.1 Stimuli

A stimulus is anything that can trigger a physical or behavioral change. In psychophysical studies, stimuli are carefully designed to manipulate specific sensory attributes or dimensions, such as intensity, duration, frequency, spatial location, or pattern. The goal is to systematically vary these attributes to examine how they influence participants' perceptual experiences or behavioral responses.

((a)) *Landolt C - Stimulus used in the psychophysical experiment.*

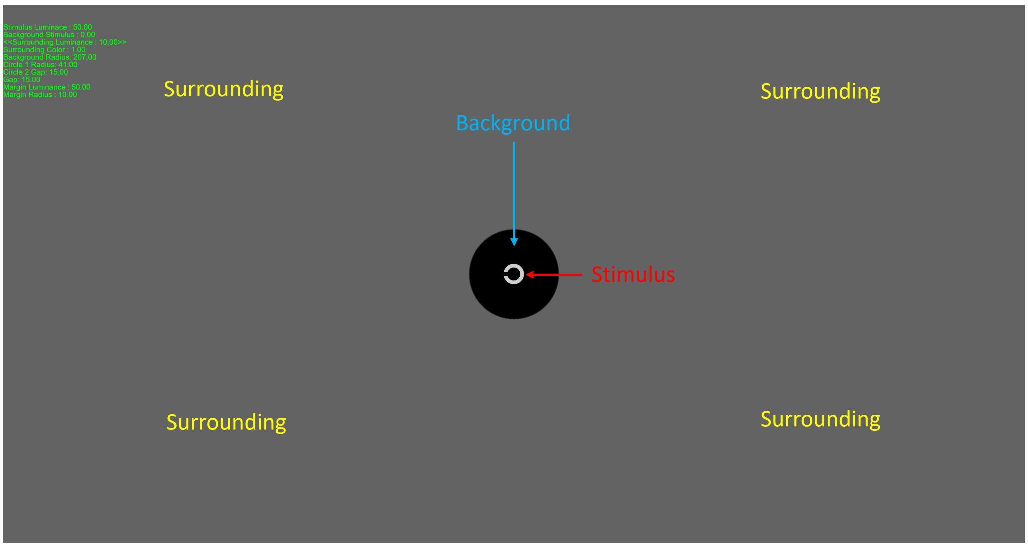
((b)) *Different orientations of Landolt C with one gap(openineg).*



((c)) *Different orientations of Landolt C with two gaps(openings).*

Figure 3.8: *Stimuli used in psychophysical experiment.*

The primary objective of this experiment was to investigate the behavior of the human visual system in relation to luminance adaptation and its impact on the contrast thresholds. Previous studies by Kelly (1977) Kelly (1974) have extensively used Gabor patterns to study contrast thresholds, which also allowed for exploring the frequency of stimuli. However, in this study, the focus was on examining the contrast threshold independently of frequency. To achieve this, the Landolt C stimulus, depicted in Figure 3.8(a), was chosen as the primary stimulus for this experiment. The motivation for using the Landolt C stimulus was derived from a study by Westheimer and McKee (1975), which demonstrated that good visual acuity does not necessarily require a stationary retinal image, here the Landolt C stimulus was modified by introducing gaps in four different directions, as illustrated in Figure 3.8(b). Another reason for using Landolt C as stimuli with varying orientations of gap openings was to mitigate potential response biases among observers, as observers were required to accurately identify the direction of gap openings if they find gaps visible.



```
Stimulus Luminace : 50.00
Background Stimulus : 0.00
<<Surrounding Luminance : 10.00>>
Surrounding Color : 1.00
Background Radius: 207.00
Circle 1 Radius: 41.00
Circle 2 Gap: 15.00
Gap: 15.00
Margin Luminance : 50.00
Margin Radius : 10.00
```

Figure 3.9: *Experiment setup shown on display to an observer while doing experiment, this image was generated with the help of SimulationCode. Green text on top right was invisible in real experiment.*

This psychophysical study employed various stimuli, as illustrated in Figure 3.8, with their sizes carefully adjusted to fall within the foveal view of the human eye at a distance of 40cm from display monitor to human eyes as shown in Figure 3.10, corresponding to approximately 2° of visual angle. The dimensions of the stimuli, including the size, ring width, and gap size, were determined using the previously mentioned Matlab simulation, ensuring standardized parameters across the experiment. To maintain a consistent contrast throughout the study, the luminance of the stimuli was fixed at 0.07 cd/m^2, allowing for the observation of the human visual system's perception with adaptation to the surrounding luminance.

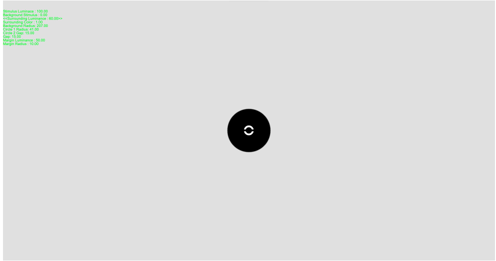
Figure 3.10: *Experiment setup with display, chin rest and observer.*

3.2.2 Background

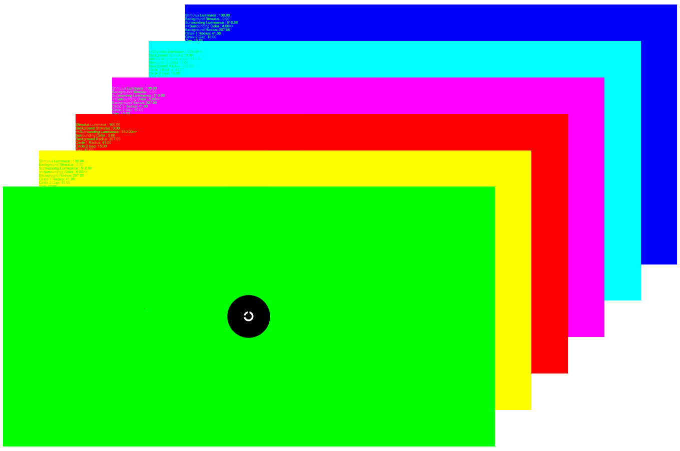
In the psychophysical experiment, the stimulus was displayed in the center of a circular background, as depicted in Figure 3.9. The stimulus had a fovial view of 10° of visual angle and was viewed from a distance of 40cm between the observer and the HDR display. To simulate simultaneous contrast, a black background with a luminance of 0.03 cd/m^2 was used in the study. The choice of a circular background was motivated by the circular shape of the stimulus, which created perceptual uniformity and a sense of completeness between the stimulus and the background. Additionally, using a circular background helped minimize peripheral visual information that could potentially influence the observer's responses. The use of a circular background is a common practice and has been employed in numerous studies on color appearance models Fairchild (2013).

3.2.3 Surrounding

The term "surrounding" refers to the field outside the background, as defined in the literature Fairchild (2013). In the context of this study, the surrounding refers to the area of the display monitor that is distinct from both the stimulus and the background, as illustrated in Figure 3.9. In practical terms, the surrounding can also encompass the broader viewing environment in which the stimuli are observed, such as the entire room. Thus, specifying the characteristics of the surrounding is of utmost importance in psychophysical experiments.



((a)) *Achromatic surrounding.*



((b)) *Chromatic Surroundings.*

Figure 3.11: *Surroundings used in the experiment*

In this particular study, the experiment was conducted in a dark room with all lights turned off, ensuring an absence of ambient light. The surrounding plays a crucial role in this study as it is utilized to investigate the luminance adaptation of the human visual system (HVS) under different color conditions, as depicted in Figure 3.11. Initially, the experiment focused solely on the use of an achromatic surrounding. However, as the experiment design progressed, there arose a curiosity regarding the potential influence of different colors in the surrounding on luminance adaptation and the resulting variations in observer responses. Consequently, the chromatic aspect of the experiment was introduced. Nonetheless, this introduction of chromatic surroundings brought about certain color-related effects, such as afterimage effect and glare induction. To mitigate these effects, a blank (dark) screen was introduced for the brief intervals while switching between two surrounding colors, as further detailed in the experiment flow section.

3.2.4 Luminance and contrast

Luminance and contrast are central to this study, with a specific focus on luminance adaptation in the presence of a constant contrast threshold between the stimuli and the background. The contrast level is fixed at 0.07 cd/m^2, where both the luminance of the stimulus and the background are set to 0.1 cd/m^2 and 0.03 cd/m^2, respectively. However, the luminance of the surrounding gradually increases throughout the experiment based on the observer's responses until it reaches a threshold point where the observer can no longer perceive the contrast.

3.3 Experiment flow

This section provides a detailed description of the experiment's code of conduct and the steps followed by each observer. Observers began by signing a participant consent form (see Appendix A), granting permission for their data to be used in the experiment. They then completed a visual acuity test, followed by a color blindness test. A brief training session was conducted to familiarize the observers with the experiment, leading to the final phase: the actual experiment.

3.3.1 Visual acuity test

Visual acuity, which refers to the ability of the visual system to perceive fine details, is assessed through a visual acuity test. This procedure is conducted to evaluate the clarity and sharpness of an individual's vision, specifically their ability to discern objects and distinguish fine details at a specific distance. Commonly, visual acuity tests involve reading standardized charts, such as the Snellen or logMAR chart, at varying distances.

In the context of the experiment, the visual acuity test served as a crucial preliminary step to ensure that each observer possessed normal or corrected-to-normal vision. This step was necessary as visual acuity plays a significant role in accurately perceiving and discriminating stimuli, which can influence the outcome of the experiment. Furthermore, establishing a consistent visual acuity level among all observers helped establish a standardized baseline for data analysis and interpretation, mitigating the potential influence of variations in visual acuity.

To conduct the visual acuity test, each observer was presented with the logMAR chart, as depicted in Figure 3.12, and positioned at a distance of 10 feet away from the chart. By identifying and correctly perceiving the letters on the chart from the designated distance, it was ensured that each observer possessed 6/6 normal or corrected-to-normal vision before proceeding with the actual experiment.

Figure 3.12: *Visual acuity board (logMAR chart) used for the visual acuity test.*

3.3.2 Color blindness test

A color blindness test, also known as a color vision test, is used to assess an individual's ability to perceive and distinguish different colors accurately. It assesses the functioning of the visual system's color receptors, known as cones, and identifies any deficiencies or abnormalities in color vision. One common color vision test is the Ishihara test Clark (1924), which uses plates with patterns of colored dots to determine the observer's ability to discern numbers or shapes embedded within the pattern.

Including a color vision test in the experiment was important to ensure that participants had normal color vision or were aware of any color vision problems they might have. This was necessary because the experiment involved tasks that required recognizing and distinguishing colors. By knowing the participants' color vision status, be it normal or impaired, potential variations in color perception could be adequately controlled, leading to accurate result interpretation. It also helps to understand how color vision issues might affect participants' responses or experiences during the experiment.

Prior to engaging in the actual experiment, each observer was required to undergo a color blindness test, specifically the Ishihara test conducted using the

Quickeval software Van Ngo et al. (2015). This initial assessment facilitated the identification of color vision anomalies, establishing a foundational understanding of the observer's color perception capabilities for subsequent analyses.

3.3.3 Training

A training session before a psychophysical experiment is crucial to familiarize participants with tasks, procedures, and goals. It provides instructions, demonstrates the setup, and promotes understanding. Participants practice and improve their performance, reducing errors. Questions and concerns are addressed, ensuring clarity. The training session enhances reliability and validity by standardizing understanding and performance, minimizing variations. It enables a smoother and more effective experiment, ensuring accurate data collection and meaningful analysis.

In this specific experiment, a small training session was conducted using Matlab, focusing on an achromatic surrounding color and presenting 20 stimuli. The purpose was to familiarize the observer with the experimental procedure and their response to the stimuli. The observer was supervised during this session to assess their understanding and performance. During the training session, the observers were given the following instructions to understand the process of the experiment:

You will see a ring type circle having either one opening or two in four directions like up, down, right and left. At same time it is also possible to see two openings i.e up and down, or up and left. Once you see the openings you have to press the arrow keys of keyboard in the same direction of openings then press space that is next to see a new ring. Order of keys doesn't matter; if openings are up and left, it is okay to press up-arrow key then left-arrow key or left-arrow key then up-arrow key. If there is a point where you can't see any opening, it is advised to wait for 5 10 seconds, and even if you do not see after this wait then press Enter and press Space. If you make a mistake; you pressed wrong arrow key, then you can reset it by pressing 0 key then Space, you will see the same ring again.

After the training session, the observers were asked if they understood the experiment process and if they had any further questions or concerns before starting the real experiment. It was ensured that the observers had a clear understanding of the experiment and knew how to proceed before commencing the actual experiment.

3.3.4 Main experiment

The experiment took place in a controlled environment, specifically a dark room where external light sources were eliminated. Observers were positioned using a chin rest as shown in the Figure 3.10, ensuring a consistent distance of 40 cm from the display. The chin rest was adjusted vertically to align the observer's sight level with the stimulus level on the display; line between eyes should be almost perpendicular to the center of stimulus, guaranteeing that the stimuli fall within the observer's foveal view.

The experiment began by presenting one of the seven surrounding colors randomly selected, as depicted in Figure 3.11. The observer's task was to provide responses until reaching their threshold for that specific color. The increment step size depended on the cumulative number of correct answers until the observer made a mistake, indicating the threshold had been reached. To determine the threshold, a step-wise algorithm was employed, inspired by the contrast sensitivity function (CSF) work Kelly and Savoie (1973). This algorithm used a stair-case approach, incrementing the surrounding stimulus with each correct response. An attempt was made to use the QUEST algorithm Watson and Pelli (1983), but it was not suitable for this experiment's requirements. The chosen algorithm allowed for smaller steps initially, leading to larger steps and finally smaller steps again to reach the thresholds. Unlike QUEST, which starts from higher values and progresses to lower values, this experiment required the opposite approach.

Following this, a blank screen was displayed for 10 seconds to minimize the afterimage effect of the human visual system (HVS). This allowed for de-adaptation to the previous color and reduced the visibility of afterimages. Subsequently, the stimuli were presented in the background in 10 steps over a 10-second period until the surrounding luminance reached a predetermined level, that is a level under which observer always perceive the contrast between stimuli and background. The chosen baseline luminance in experiment was approximately half of the actual baseline luminance to account for observer adaptation to the surrounding color and luminance. This decision was made as a trade-off between the duration of the experiment and providing sufficient time for observers to adapt to the specific surrounding color and luminance conditions. The intention was to strike a balance between optimizing experimental efficiency and ensuring reliable perception of contrast.

So overall, a 20-second gap was introduced between two surrounding colors to address effects like the afterimage phenomenon, provide rest to the eyes to mitigate fatigue, and ensure the eyes were less adapted to the previous surrounding color. The next surrounding color was randomly selected to ensure independence of results from the previous color, as observers could still be adapted to the previous color state. Additionally, one surrounding color was repeated twice in the experiment to investigate both intra-observer variations and observe differences in thresholds for the same color.

In the experiment following data was collected from each observer as shown in table 3.4.

Table 3.4: *Data collected through the psychophysical experiment.*

Feature	Description
Surrounding luminance	Luminance of surrounding at each stimulus
Step size	Step size between two stimuli
color	Surround color at which stimulus was shown
Displayed opening	Openings shown in the stimuli on display
Observer response	Response of observer about the directions of openings
Time	Time taken at each stimulus

4 Results

Science never gives up searching for truth, since it never claims to have achieved it.

John Polanyi

This study involved the implementation of a psychophysical experiment, and this section provides a detailed analysis of the obtained results.

4.1 Experiment essentials

This section provides a comprehensive overview of the key concepts that are essential for comprehending the outcomes obtained from this experiment.

4.1.1 Observers

The experiment involved a cohort of 30 participants, comprising 19 males and 11 females. The study consisted of three distinct age groups: a group of 14 young subjects, ranging from 20 (inclusive) to 30 (exclusive) years old, with an average age of 24 years; a group of middle-aged subjects, ranging from 30 (inclusive) to 40 (exclusive) years old, with an average age of 34 years; and a group of 4 elderly subjects, aged 40 years and above, with an average age of 52 years. All observers possessed normal color vision as determined through the Ishihara test with the assistance of quickeval.

The data collected by an observer is presented in Figure 4.1. The experiment commenced with a minimal level of surround luminance, and as a result of accurate

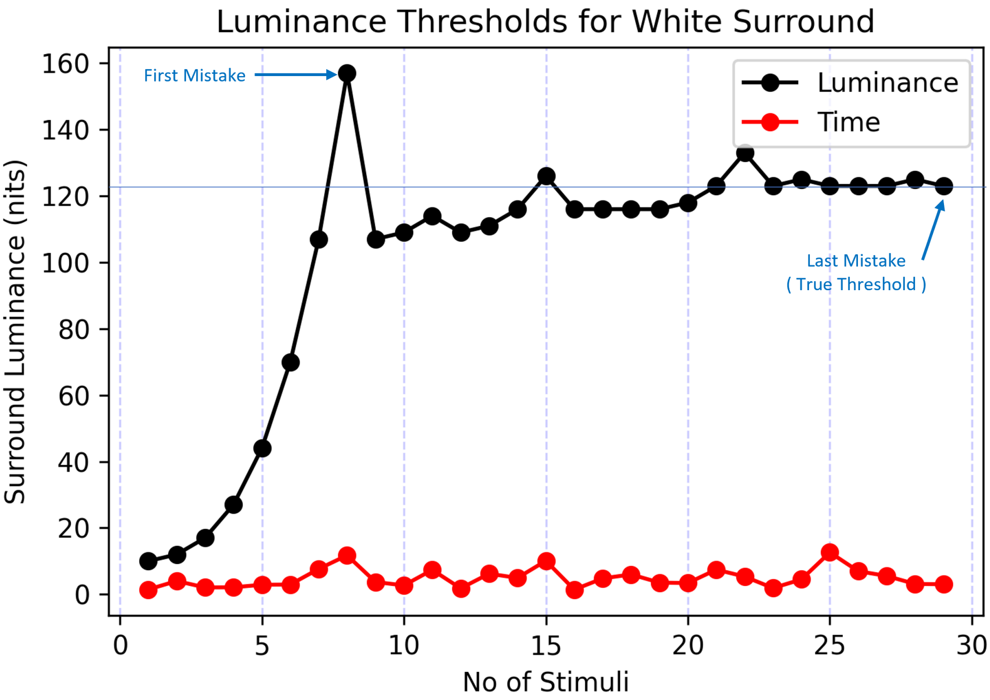


Figure 4.1: *The graph depicts the luminance threshold achieved by a single observer against a white surround. The peaks on the graph represent the mistakes made by the observer. Blue arrows pointing towards the first and last mistake (true threshold). The red line represents the duration of time taken by the observer for each stimulus.*

anticipation of stimulus gaps by the observer, the surrounding luminance gradually increased until it reached a threshold. At the 8^{th} stimulus in graph, a mistake was made by the observer, prompting a return to the previous state which can be observed in the case of highest peak of the graph. Subsequently, smaller increments were made in an effort to approach the observer's true threshold, as depicted in Figure 4.1. The red line represents the duration of time it takes for the observer to respond to each stimulus. The data reveals that the observer allocated a greater amount of time to stimuli associated with incorrect responses, indicating a difficulty in answering those specific stimuli and suggesting proximity to the observer's threshold.

4.1.2 Color values to reproduced brightness

The luminance in the CIE system of colorimetry is defined as the Y tristimulus value Wyszecki and Stiles (2000). Luminance can be regarded as a measure of the effectiveness of different wavelengths of stimuli in producing the sensation of brightness. Consequently, it is reasonable to infer that the Y tristimulus value provides a direct assessment of perceived brightness Fairchild (2013). However, the Helmholtz-Kohlrausch color effect has disproved this phenomenon, asserting that the perceived brightness of stimuli is dependent upon both their luminance and chromatic properties. It has been indicated that when the stimulus becomes more chromatic while maintaining a constant luminance, it is perceived as being brighter.

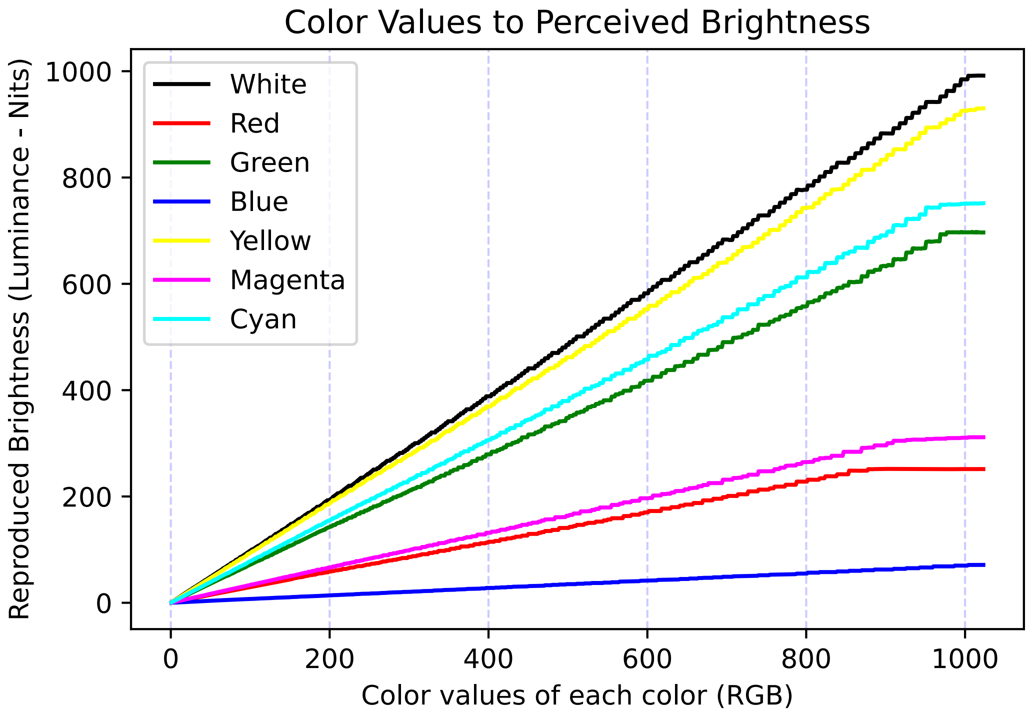


Figure 4.2: *Relationship between color values and its luminances on HDR screen for each color used as Surround in experiment. Luminance was captured by Konica Minolta CS-2000.*

In addition, the spectroradiometer Konica Minolta CS-2000 was used to estimate the luminance of all color values within the 10-bit HDR pipeline utilized in this study, as depicted in Figure 4.2. This data indicates that White (represented by black color in the graph) exhibits the highest luminance, while blue demonstrates the lowest luminance. This can be attributed to the fact that the human visual system (HVS) is more sensitive to white color, which stimulates all three types of cones. In contrast, blue color primarily stimulates the short wavelength cones.

$$Luminance(Y) = Red * 0.2169 + Green * 0.7235 + Blue * 0.0596 \tag{4.1}$$

The determination of luminance (Y tristimulus) can be achieved using the CIE system of colorimetry, utilising Equation 4.1 as presented in table 4.1 as objective brightness. The reproduced brightness was determined using a spectroradiometer, revealing a noticeable difference between both brightness values. This potential difference can be the device error of Konica Minolta itself, as in calculation of such readings, geometry of capturing device, luminance, illuminace, ambient light, and some other factors can affect it.

Table 4.1: *The perceived brightness of maximum RGB values of each color is determined through the utilisation of Equation 4.1 to calculate the objective brightness, and subjective brightness was determined by employing a spectroradiometer.*

Surround colors	Objective Brightness	Reproduced Brightness
White	991.67	991.67
Red	215.09	251.52
Green	717.47	696.64
Blue	059.10	071.26
Yellow	932.56	930.13
Magenta	274.19	311.49
Cyan	776.57	751.66

4.1.3 Inter and intra observer variations

Inter and intra observer variation is a metric utilised to comprehend the conduct of observers' responses within an experiment. It serves as a quantitative indicator of the reliability and consistency of observer responses. Intra-observer variance refers to the degree of variation in observer responses within an experiment when the same stimulus is presented under identical conditions. In this particular experiment, each surround color was repeated twice, allowing for the calculation of intra-observer variation by comparing the observer responses across both surround colors. Where as, inter-observer variance refers to the degree of variation in all the observers' responses within an experiment when the same stimulus is presented under identical conditions to each observer.

$$RMSE = \sqrt{\sum_{i=1}^{n} \frac{(A_i - B_i)^2}{n}} \tag{4.2}$$

The root mean square error (RMSE), as expressed in Equation 4.2, was employed to quantify both the intra and inter observer variance. A higher rmse value indicates a significant discrepancy between two variables.

Table 4.2: *Intra observer variance of each color used in the experiment as surround.*

Surround color	Intra-Observer RMSE
White	30.223
Red	42.982
Green	37.675
Blue	07.019
Yellow	34.257
Magenta	20.516
Cyan	35.158

In the case of intra observer variance, A and B data in Equation 4.2 were the luminance thresholds obtained by both surround colors, as same surround color was repeated for each observer. Intra observer variance values for each color are mentioned in Table 4.2, revealing that observers demonstrated greater consistency when perceiving the blue surround color, as indicated by its lowest root mean square error (RMSE) value. Conversely, observers performed less reliably when perceiving the red surround color, as evidenced by its highest RMSE value. Moreover, we can also demonstrate the results in other way that observers were not getting that much adapted in blue surround color as blue has lowest perceived brightness value than other colors as discussed above and it is also complimented by H-K effect that blue in comparison to other colors has lowest perceived brightness Ullah et al. (2022).

In the case of inter observer variance, A and B in Equation 4.2 data were the mean and individual observer's results. The inter-observer variance values for each color are presented in Table 4.3, where the first-order column corresponds to the results associated with the appearance of the first surround colors, and the second-order column corresponds to the results obtained when the same surround color reappeared in the experiment. The data in this table again compliments the same results which were observed in the case of intra observer variance, blue surround color shows highest response agreement among all the observers and red surround color shows the highest response disagreement among all the observers.

Table 4.3: *Inter observer variance of each color used in the experiment as surround. 1st order represents the RMSE values when surround color was appeared first time in experiment and 2nd order represents when surround color appeared again in the experiment.*

Surround color	1st Order	2nd Order
White	47.325	51.458
Red	71.846	78.076
Green	63.394	55.352
Blue	15.686	18.178
Yellow	51.987	51.816
Magenta	40.840	44.994
Cyan	61.213	62.787

As both intra and inter observer variance results representing same insights so this further compliments that these insights were not only because of inconsistency between observers' responses but there must be another phenomenon which is common between all the observers, that could be luminance adaptation.

Furthermore, Figure 4.3 presents a graphical depiction of the luminance thresholds of all observers, providing insight into the variability among these thresholds. The data indicates that the mean values of blue are nearly identical in both orders of the surrounding color, thus corroborating the quantitative findings regarding the blue surround color discussed earlier. In contrast, the color green exhibits more pronounced shifts in mean values for both surrounding colors. This observation contradicts the quantitative findings mentioned earlier. However, it is important to note that this visual representation does not specifically depict the extent of variation among observers or within individual observers. Rather, it primarily reflects the dispersion of the data. Another insight that can be extracted from presented figure is that the green and cyan colors exhibit the highest perceived luminance thresholds in comparison of the other surround colors.

4.2 Initial and final mistakes thresholds

The present study examines the luminance threshold and investigates situations where an observer does errors during the experiment. These errors indicate that the observer has either already reached or is on the verge of reaching their potential threshold. This section provides additional details regarding the initial and final mistakes made by observers during the course of the experiment, as previously discussed in the preceding section. The final errors correspond to the luminance

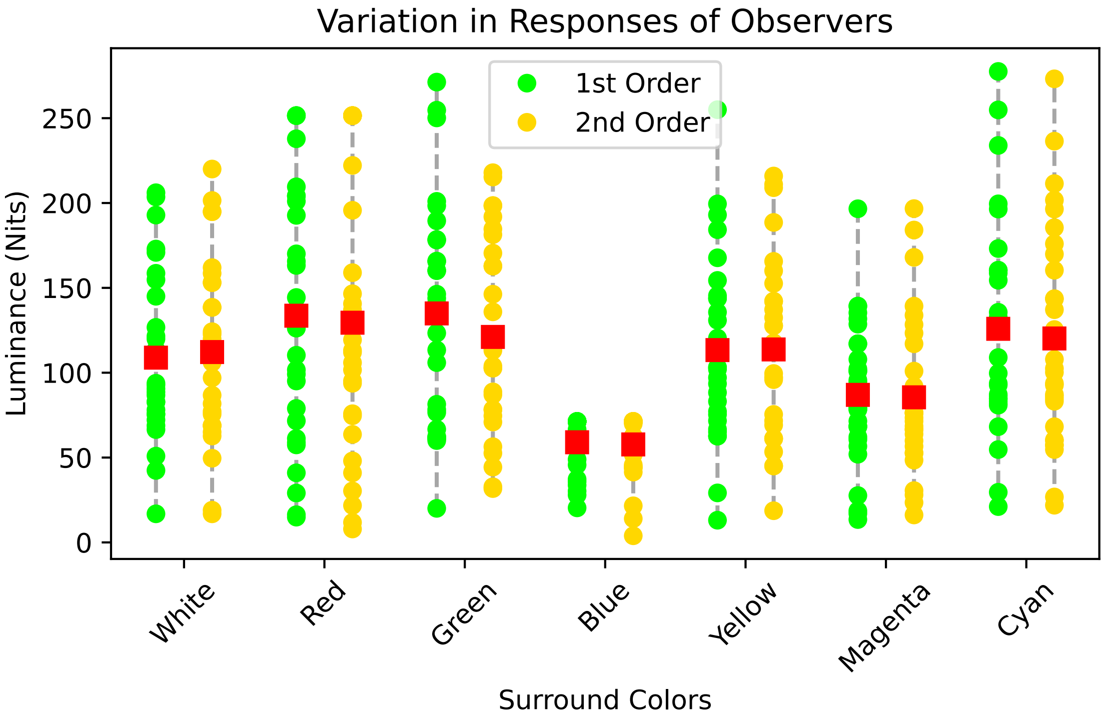
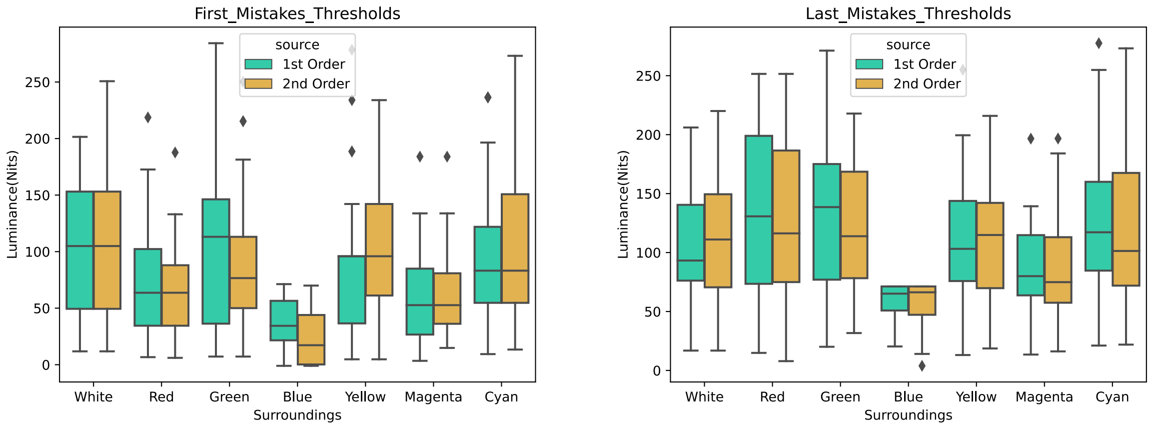


Figure 4.3: *Variation in the luminance thresholds for each color achieved by all the observers in the experiment. Here, red square represents the mean of all the responses. Legend shows the order in which same surround color appeared in experiment.*

thresholds of the observers. The box plot in Figure 4.4 displays the first and last mistakes made by observers for each surround color depicted on the x-axis. Additionally, the box plot includes the mistakes made in repeated surround colors, with each category of surround color on the x-axis represented by two box plots. It was found that only achromatic surround color (white) follows the expected behavior, true threshold (last mistake) should be lower than initial mistake, as observer could not see the gap at initial mistake, causing surround luminance level to return to a lower luminance level and subsequently take smaller steps of luminance in order to reach the true luminance threshold. It can only be observed in the case of first order of achromatic colors from the Figure 4.4(a) and 4.4(b), where as in the case of second order of achromatic color true threshold is higher than the first mistake. It can also be observed from the Figure 4.4(a) and 4.4(b) that in the case of chromatic surround colors all of them have not followed the expected behaviour; true thresholds are higher than the initial mistakes. Moreover, it can be deduced that performance of all the observers was influenced during the



((a)) *First mistakes done by the observers while doing the experiment.*

((b)) *Last mistakes which also represents the luminance thresholds of all the observers.*

Figure 4.4: *Luminance thresholds represented by box plots to show the dispersion of the responses of observers.*

experiment with time; they started perceiving the gaps in luminance levels higher than their initial mistakes, indicating the presence of a shared phenomenon among all the observers, which might be due to luminance adaptation.

Table 4.4: *Left: Descriptive statistics of luminance thresholds (final mistakes) for all surround colors at second order (sequence). Right: One way ANOVA results between all surround colors.*

color	Mean	Std. Dev.	Std. Error
White	108.87	48.13	08.78
Red	133.60	73.07	13.34
Green	134.94	64.48	11.77
Blue	059.01	31.95	06.91
Yellow	113.33	52.88	09.65
Magenta	086.94	41.54	07.58
Cyan	125.86	62.25	11.36

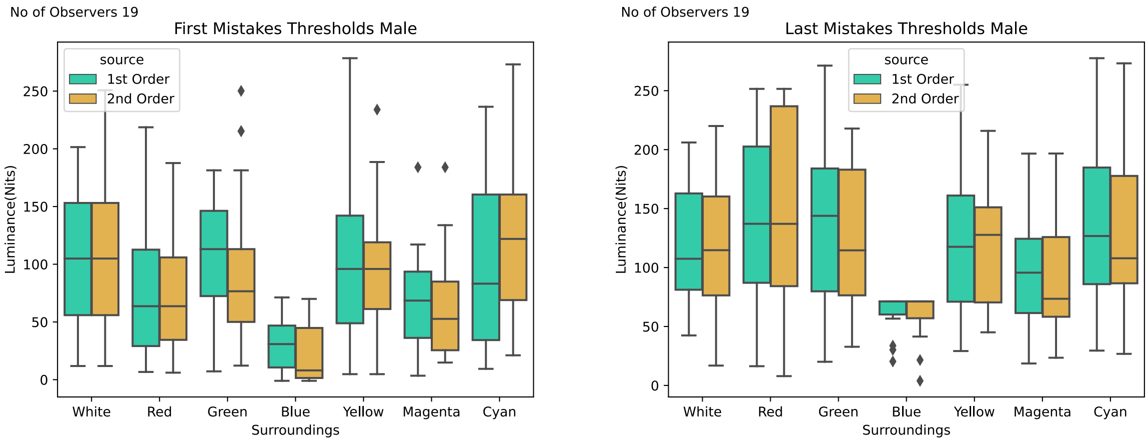
F-Stat	P-Value
7.8094	0

The presence of luminance adaptation was observed in all surrounding colors, although the degree of adaptation varied among all the surround colors, especially in the red, green, and blue surround colors. The color red is indicative of the highest level of adaptation observed during the experiment, while yellow is representative of the lowest level of adaptation observed during the experiment. The observed outcomes appear to align with the conclusions drawn by High et al. (2023) in their study on the Helmholtz-Kohlrausch (H-K) effect. High et al. (2023) found that the color yellow exhibits the lowest perceived brightness due to negligible H-K effect, while the red hue demonstrates a relatively high perceived brightness due strong H-K effect. The effect of H-K in yellow implies that as the colorfulness of the yellow surround increases, its perceived brightness will not increase to the same extent as it would with other surround colors. Consequently, the human visual system (HVS) will not adapt as strongly to a yellow surround compared to other colors, resulting in a lesser degree of adaptation as indicated by the Figure 4.4. In the context of red surround color, H-K effect is higher; perceived brightness will be increasing with increment of colorfullness, so HVS will also adapt more to luminance than other surround colors resulting in higher shifts in luminance thresholds, which compliments our findings. Furthermore, the statistical analysis includes the calculation of mean, standard deviation, and standard error for the true luminance thresholds at the second order of surround color. These results are presented in Table 4.4 in order to assess the statistical significance. It is evident from the table that the color blue exhibits the lowest standard error, while the color red exhibits the highest standard error. A One-way Analysis of Variance (ANOVA) was performed to analyse the data for all surrounding colors. The results of this analysis can be found in Table 4.4 on the right side. The F-statistic measures the variability between the means of different groups relative to the variability within each group. The *p-value* represents the probability of observing the obtained F-statistic assuming that the null hypothesis (which states that there are no significant differences among the means of the groups) is true. A *p-value* of 0 indicates a statistically significant difference among all surrounding colors. It is important to note that one-way ANOVA does not directly assess the significance between all groups, but rather determines whether there is any significant difference present.

4.2.1 Gender based segregation

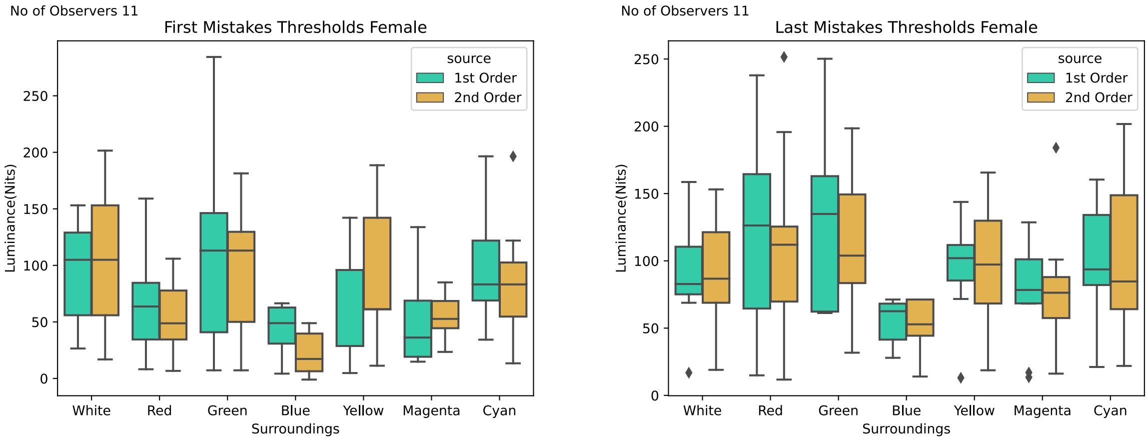
The initial and final mistakes were further segregated gender wise in two classes; males and females as depicted in Figure 4.5. One general trend devised from these graphs is that males have higher threshold levels than females, but we can not generalize this trend with these results acquired from a small and imbalanced number of observers; 30 observers with 19 males and 11 females.

Furthermore, it is evident from Figure 4.5(a) and 4.5(b) that males exhibit a similar pattern as the overall data, as discussed earlier when examining the overall results. Highest adaptation has been achieved in red surround color by males; there are higher shifts between initial and final mistakes done by males in red surround color. And lowest adaptation can be observed in yellow surround color; similar



((a)) *First mistakes done by the male observers.*

((b)) *Last mistakes (luminance thresholds) done by all male the observers.*



((c)) *First mistakes done by the female observers.*

((d)) *Last mistakes (luminance thresholds) done by all female the observers.*

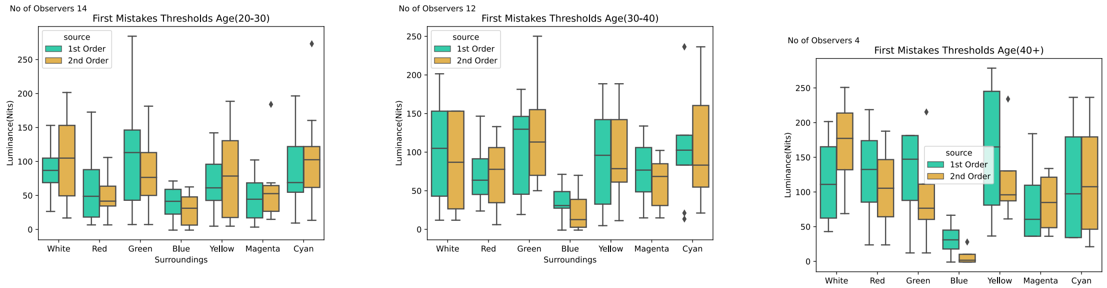
Figure 4.5: *Luminance thresholds represented by box plots segregated by gender to show the gender wise dispersion of the responses of observers. Number of males and females are shown in the top left of each graph.*

luminance thresholds in initial and final mistakes have been achieved by male observers in the case of yellow surround color. In the case of female participants, it is evident from Figure 4.5(c) and 4.5(d) that they exhibit a similar pattern as males, with higher luminance thresholds during final mistakes compared to initial mistakes. However, the magnitude of this shift is comparatively smaller for females. It is noteworthy that, when considering the achromatic surround color (white), females exhibit higher threshold values for initial mistakes compared to final mistakes. This observation implies that females may not undergo as much luminance adaptation as males do in the context of achromatic surround color, based on the current data obtained from the experiment.

4.2.2 Age based segregation

The initial and final mistakes were segregated further in three age groups; a group of 14 young subjects, ranging from 20 (inclusive) to 30 (exclusive) years old as shown in Figure 4.6(a) and 4.6(d); a group of middle-aged subjects, ranging from 30 (inclusive) to 40 (exclusive) years old as shown in Figure 4.6(b) and 4.6(e); and a group of 4 elderly subjects, aged 40 years and above as shown in Figure 4.6(c) and 4.6(f). One notable observation that can be made from all the graphs presented in Figure 4.6 is that the thresholds for both the order of surround color exhibit significant differences. This finding suggests that either the responses of the observers were inconsistent or there were other factors influencing the responses, such as luminance adaptation. Another notable observation is that there is a general trend indicating an increase in luminance adaptation thresholds with age. However, this trend seems counter intuitive, as younger individuals typically exhibit better visual acuity compared to older individuals under normal circumstances. There are several potential factors contributing to the observed disparity. Firstly, it is important to acknowledge that the sample size of elder observers is limited to only four individuals, which restricts the generalizability of the findings. Additionally, it is worth noting that all four elder observers were professors and had a basic knowledge of the field of color science, so they had a better understanding of HVS than normal observers, potentially introducing a bias into their results.

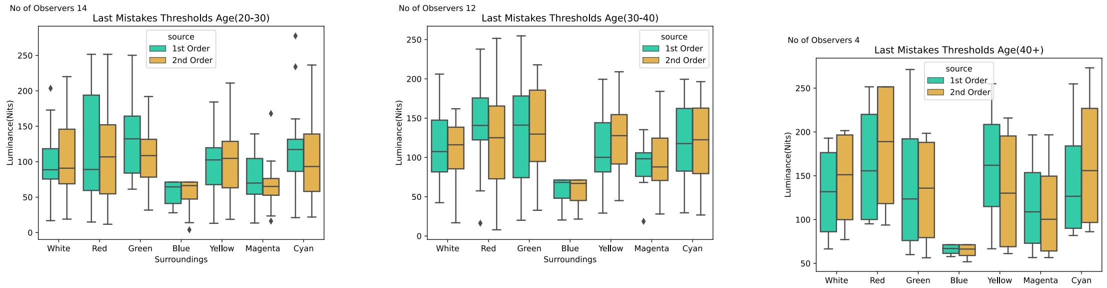
Further, it can also be observed that age based graphs follows the same trend of color surround based adaptation; red surround color showing higher luminance adaptation than other surround colors and yellow having lower luminance adaptation than other surround colors.



((a)) *First mistakes done by the observers with age between 20(included) to 30(excluded) years.*

((b)) *First mistakes done by the observers with age between 30(included) to 40(excluded) years.*

((c)) *First mistakes done by the observers with age between 40 years and above.*



((d)) *Last mistakes done by the observers with age between 20(included) to 30(excluded) years.*

((e)) *Last mistakes done by the observers with age between 30(included) to 40(excluded) years.*

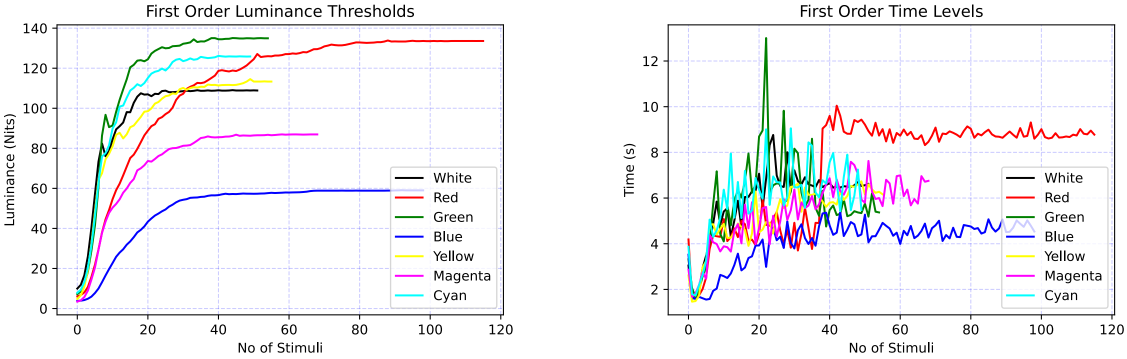
((f)) *Last mistakes done by the observers with age between 40 years and above.*

Figure 4.6: *Luminance thresholds represented by box plots segregated by age groups to show the age wise dispersion of the responses of observers. There are three age group, young, middle-age and elders. Number of observers are shown in the top left of each graph.*

4.3 Luminance thresholds

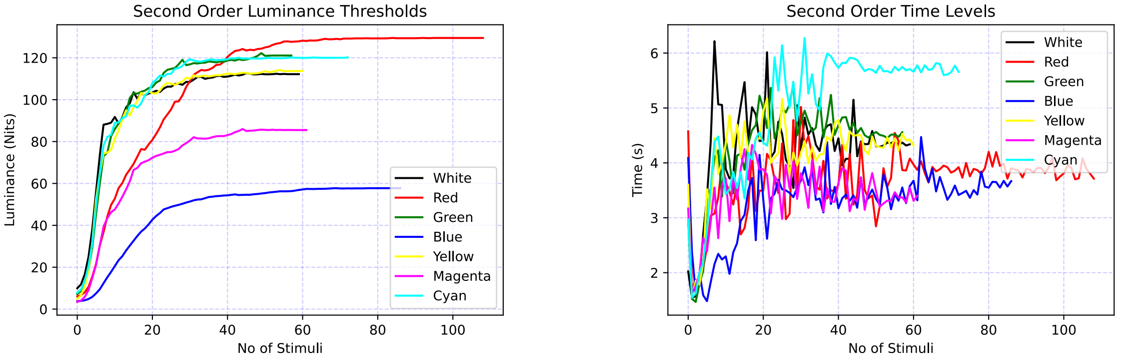
In this study observer's data was achieved in a way that was discussed above in section 4.1.1 and depicted in Figure 4.1. An average of all such observers' data both in luminance threshold and time taken at each stimulus, were calculated and depicted in Figure 4.7 for all the surround colors. As the same surround color was repeated twice in the experiment, that is why there are two graphs of both luminance thresholds and time taken by observers during experiment in Figure 4.7.

One general trend that we can observe from this visual depiction is that, it took highest number of stimuli in red surround color to reach a threshold than other surround colors, on second number it is blue surround color that took second highest number of stimuli to reach a threshold. But in the case of blue surround



((a)) *Average luminance thresholds achieved by all observers during the first order of surround color.*

((b)) *Average time taken by all observers during the second order of surround color in experiment at each stimulus.*



((c)) *Average luminance thresholds achieved by all observers during the second order of surround color.*

((d)) *Average time taken by all observers during the second order of surround color in experiment at each stimulus.*

Figure 4.7: *Average luminance thresholds and average time taken by all the observers during the experiment.*

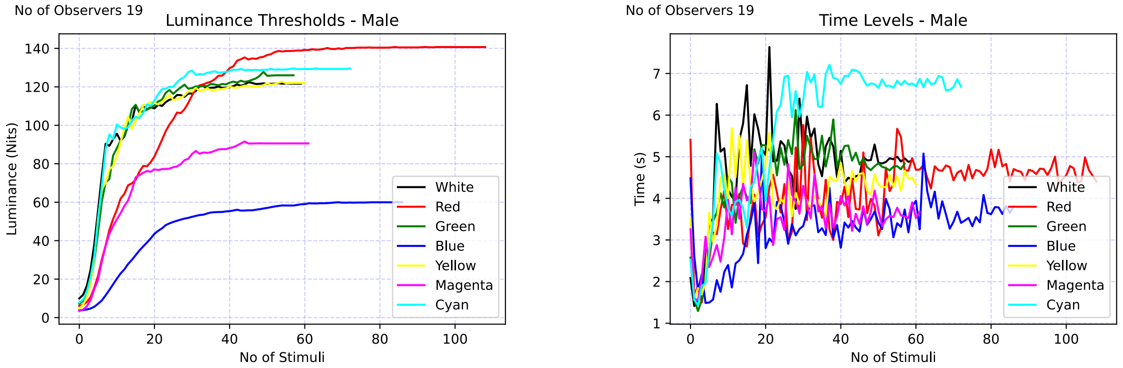
color, perceived brightness is lower than other surround colors, so it is highly like that some observers must have gone beyond the maximum luminance level that can be achieved in blue surround color, resulting in luminance threholds for these observer as maximum luminance of blue as shown in Table 4.1. It can also be observed that red has highest luminance thresholds on average than any other surround color, complimenting the previous findings of this study. Another general trend to be noticed here is in the order of surround colors depicted in Figure 4.7(a) and 4.7(c), where luminance thresholds have remained almost same except in the case of green and magenta surround colors, where thresholds were a bit higher in first order of surround color than second order, but overall this difference is not that significant.

Moreover, in the case of average time taken by observers depicted in the Figure 4.7(b) and 4.7(c), it can be observed that on average most time was spent on red surround color stimuli and less time on blue surround color stimuli, suggesting that it was difficult to perceive the gaps in red surround color and easier in blue surround color than all the other surround colors. But in second order of surround colors depicted in Figure 4.7(d), results are bit different, here most time was spent on cyan unlike to fist order of surround color but least amount was spend again on blue surround color.

4.3.1 Gender based segregation

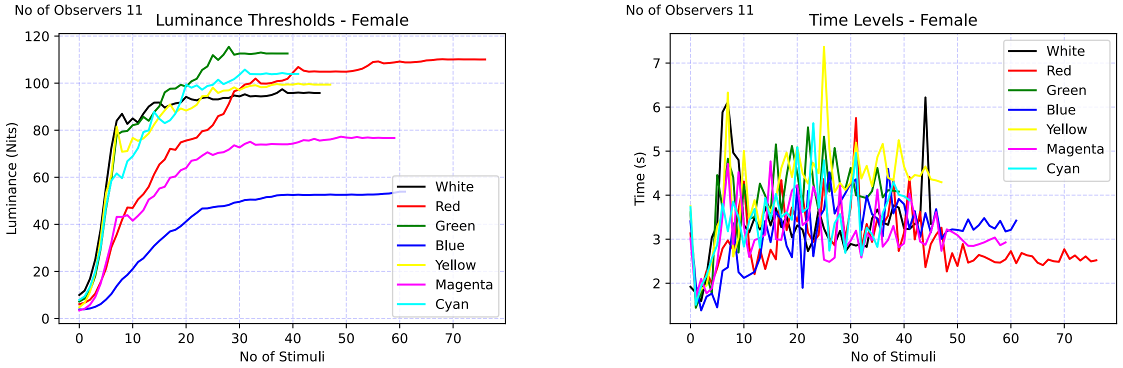
Average luminance and average time taken by observers in the experiment were further segregated gender wise in two classes: males and females as depicted in Figure 4.8. It is important to note that the results in this part are solely from the second order of surround color because the observer would have been adapted to surround color and must have got more familiar to experiment in first order of surround color. One general trend devised from these graphs is that males have higher threshold levels than females, but again we can not generalize this trend with these results acquired from a small and imbalanced number of observers; 30 observers with 19 males and 11 females. This trend is also complimenting the general trend that was observed before in gender wise segregation in initial and final mistake threshold section 4.2.

Furthermore, it is evident from Figure 4.8(a) that red surround color has the highest luminance threshold values than any other surround color in male based results, again corroborating the general trend found before from overall results that the red surround color has highest luminance thresholds and highest luminance adaptation. Time taken by male observers is depicted in Figure 4.8(b) and it can be observed that most time spent by male observers was on cyan surround color based stimuli, suggesting that it is difficult for males to perceive gaps in cyan surround color. Where as, least time was spent on blue surround color stimuli by male observers indicating that it is easier to perceive gaps in blue surround color than other surround colors of experiment. In the case of female observers, it can be observed from the Figure 4.8(c) that highest luminance threshold achieved by females is in green surround color, that is not the case in responses of males, but there is not a significant different between luminance thresholds of green and red surround colors. It can also be observed that most of surround colors have same pattern in responses of females in the comparison of responses of males, with a slight shift in luminance of responses of females.



((a)) *Average luminance thresholds achieved by male observers during the second order of surround color.*

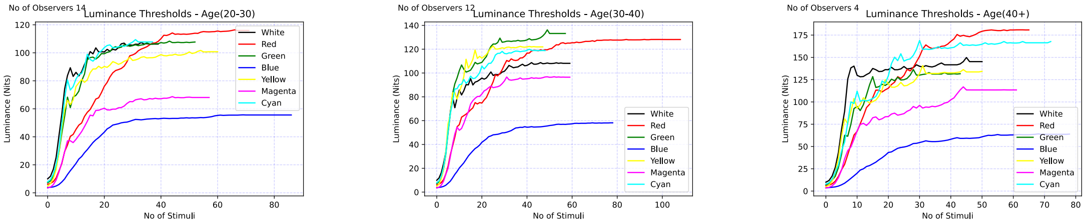
((b)) *Average time taken by male observers during the second order of surround color in experiment at each stimulus.*



((c)) *Average luminance thresholds achieved by female observers during the second order of surround color.*

((d)) *Average time taken by female observers during the second order of surround color in experiment at each stimulus.*

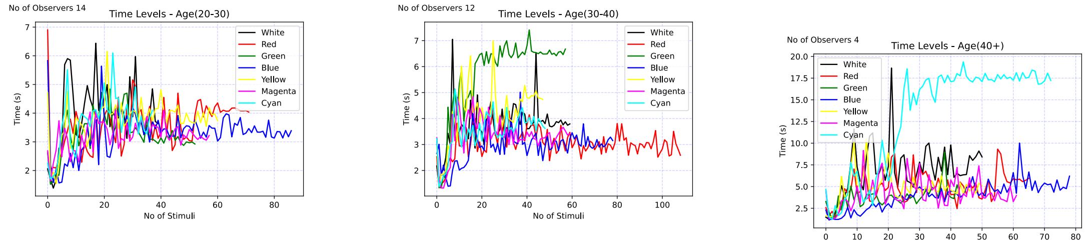
Figure 4.8: *Average luminance thresholds and average time taken by all observers segregated by gender to show the gender wise dispersion of results. Number of males and females are shown in the top left of each graph.*



((a)) *Average luminance thresholds by the observers with age between 20(included) to 30(excluded) years.*

((b)) *Average luminance thresholds by the observers with age between 30(included) to 40(excluded) years.*

((c)) *Average luminance thresholds by the observers with age of 40 years and above.*



((d)) *Average time taken by observers with age between 20(included) to 30(excluded) years.*

((e)) *Average time taken by the observers with age between 30(included) to 40(excluded) years.*

((f)) *Average time taken by the observers with age between 40 years and above.*

Figure 4.9: *Average luminance thresholds and average time taken by observers represented by line plots segregated by age groups to show the age wise dispersion of the responses of observers. There are three age group, young, middle-age and elders. Number of observers are shown in the top left of each graph.*

4.3.2 Age based segregation

Average luminance thresholds and average time taken by observers in the experiment were further segregated in three age groups; a group of 14 young subjects, ranging from 20 (inclusive) to 30 (exclusive) years old as shown in Figure 4.9(a) and 4.9(d); a group of middle-aged subjects, ranging from 30 (inclusive) to 40 (exclusive) years old as shown in Figure 4.9(b) and 4.9(e); and a group of 4 elderly subjects, aged 40 years and above as shown in Figure 4.9(c) and 4.9(f). One general observation that can be made from all the average luminance threshold graphs segregated by age is that average luminance thresholds are increasing with age. However this trend seems counter intuitive, as younger individuals typically exhibit better visual acuity compared to older individuals under normal circumstances. It is worth mentioning that this trend was also observed in previous section 4.2 age based results. Typical factors effecting these results can be small and imbalanced data of results acquired from experiment, as only 4 observer were involved in elders age group. Another factor can be pre-knowledge of the color science and HVS as all the elder observers were professor with a basic knowledge of color science, potential to introduce a bias into the results.

Another significant finding from Figure 4.9 is that the surround color with the highest luminance threshold for each age group varies. Young observers have the highest luminance thresholds in red surround color, as shown in Figure 4.9(a), whereas middle-aged observers perceive better in green surround color as shown in Figure 4.9(b) and older observers perceive better in both red and cyan surround colors, as shown in Figure 4.9(c). The graphs of the average amount of time spent on each stimulus by observers of various ages show one obvious explanation for this discrepancy. In Figure 4.9(d), it can be seen that young observers spent nearly the same amount of time on all the stimuli and surround colors, supporting the general trend of the highest luminance threshold of red surround color. While it is evident in Figure 4.9(e) that middle-aged observers spent more time on stimuli with green surround color, leading to higher luminance thresholds in green surround color, same trend can also be observed in Figure 4.9(f) where elder observers spent more time on stimuli with cyan surround color, leading to cyan surround color-based stimuli having almost the same luminance thresholds as red surround color. These results suggest that observers have higher luminance thresholds in a given surround color if they have spent more time with that surround color, giving a suggestion how luminance adaptation can effect the results.

4.4 Horizontal vs. vertical perception

The stimulus used in the conducted experiment for this study has 4 types of orientations: up, down, left and right. These stimuli orientations can be divided in two broad categories of orientations: vertical, consisting of gap openings in the stimuli towards up and down directions, and horizontal, consisting of gap openings in the stimuli towards left and right directions. There is an interesting spatial visual phenomenon called oblique effect, it states that visual acuity of HVS is better for gratings orientated at 0° or 90° than gratings orientated at other visual angle relative to the line connecting the human eyes Fairchild (2013). However, this effect does not state anything between vertical or horizontal visual acuity such as whether HVS perceive better in vertical gratings or horizontal gratings. One of findings that can be observed from the results of this experiment is whether observers have done more mistakes either in vertical gap openings or horizontal gap openings to understand further whether HVS perceive better vertically or horizontally. All the mistakes were taken into account for the results, such as, if an observer has done one correct and one wrong prediction of gap openings in a two gap openings based stimulus, then the incorrect prediction will be counted here. As an example,

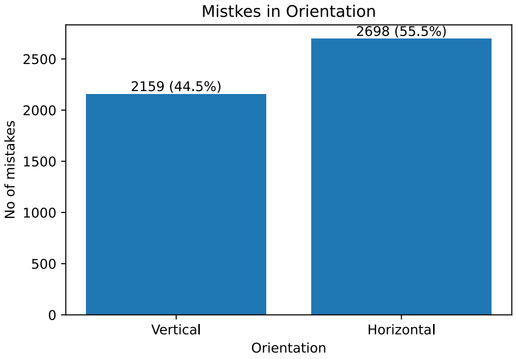
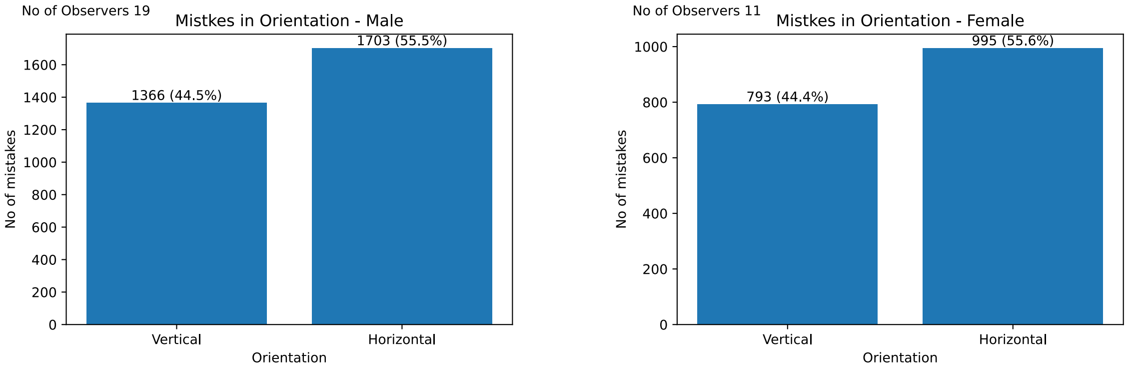


Figure 4.10: *Vertical and horizontal mistakes done in the experiment.*

if there were two gap openings in a stimulus, one at the upper position and one at the left position, and the observer correctly identified the upper opening but failed to identify the left opening, the left opening would still be included in the calculation of horizontal versus vertical perception. Moreover, it can be observed from the Figure 4.10 that all the observers have done around 24% more mistakes in horizontal direction based gap openings that vertical direction ones. So it can be inferred from these statistics that HVS perceive better in vertical direction that horizontal direction. Of course findings of this experiment can not be generalized but at least it can give a hypothesis that can be further proved by more evidences.



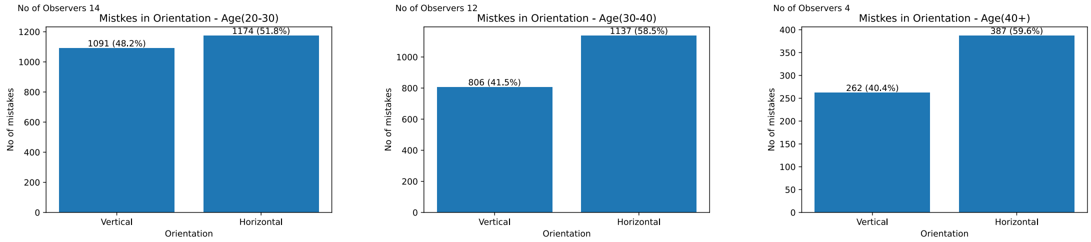
((a)) *Vertical and horizontal mistakes done by male observers in the experiment.*

((b)) *Vertical and horizontal mistakes done by females observers in the experiment.*

Figure 4.11: *Vertical and horizontal mistakes done by all observers segregated by gender to show the gender wise dispersion of results. Number of males and females are shown in the top left of each graph.*

4.4.1 Gender based segregation

Vertical and horizontal based mistakes were further segregated gender wise into two categories: males and females as shown in Figure 4.11. It can be observed that gender wise results also corroborate the same hypothesis given before that HVS perceive better in vertical direction than horizontal. Moreover, it can be observed that males have done more mistakes than females in general because number of males (19) is higher than females (11), depicted in the top left of each graph, but ratio of gender wise mistakes is same as shown in Figure 4.11(a) and 4.11(b).



((a)) *Mistakes done by the observers with age between 20(included) to 30(excluded) years.*

((b)) *Mistakes done by the observers with age between 30(included) to 40(excluded) years.*

((c)) *Mistakes done by the observers with age between 40 years and above.*

Figure 4.12: *Vertical and horizontal mistakes represented by bar plots segregated by age groups to show the age wise dispersion of the mistakes of observers. There are three age group, young, middle-age and elders. Number of observers are shown in the top left of each graph.*

4.4.2 Age based segregation

Vertical and horizontal gap openings stimuli based mistakes were further segregated in three age groups; a group of 14 young subjects, ranging from 20 (inclusive) to 30 (exclusive) years old as shown in Figure 4.12(a); a group of middle-aged subjects, ranging from 30 (inclusive) to 40 (exclusive) years old as shown in Figure 4.12(b); and a group of 4 elderly subjects, aged 40 years and above as shown in Figure 4.12(c). One general observation that can be inferred from these graphs is that in all age groups HVS has better visual acuity in vertical gratings than horizontal, but the degree of this visual acuity is different for these three age groups. It seems that young observers have almost similar visual acuity in both vertical and horizontal direction as shown in Figure 4.12(a), young observers have only done 7% higher mistakes in horizontal direction than vertical direction. Where as, middle aged group has done around 40% more mistakes in horizontal direction that vertical direction, giving a significant difference of visual acuity in both directions as shown in Figure 4.12(b). In the case of elder observers, they have done 47% more mistakes in horizontal direction than vertical direction based gap openings of stimuli as shown in Figure 4.12(c). From these results, it can be deduced that with age, HVS perceive better in vertical direction gratings than horizontal ones, or in other terms, HVS gets worse at horizontal visual acuity with age.

4.5 Horizontal vs. vertical color perception

In the previous section, gap openings orientations of stimulus used in the experiment for this study were explored, without any information of surround color. In this section surround color effect with horizontal and vertical visual acuity is explored as depicted in Figure 4.13, where all the vertical and horizontal mistakes done by the observers in each color are shown separately. One general observation inferred from the visual representation in Figure 4.13 is that, red surround color has highest number of mistakes than any other surround color and blue surround color has least number of mistakes that were done by observers while conducting the experiment, corroborating the results found in previous sections, that red surround color is difficult when it comes to perceive gaps in the stimuli, and blue is easiest to perceive the gaps in stimuli. Moreover, it can also be observed that in all the surround colors, mistakes done in horizontal orientation of gaps of stimuli are higher than vertical ones, supporting the hypothesis proposed before that, HVS has better visual acuity in vertical gratings than horizontal.

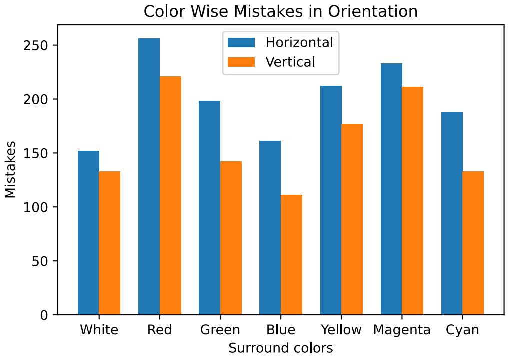
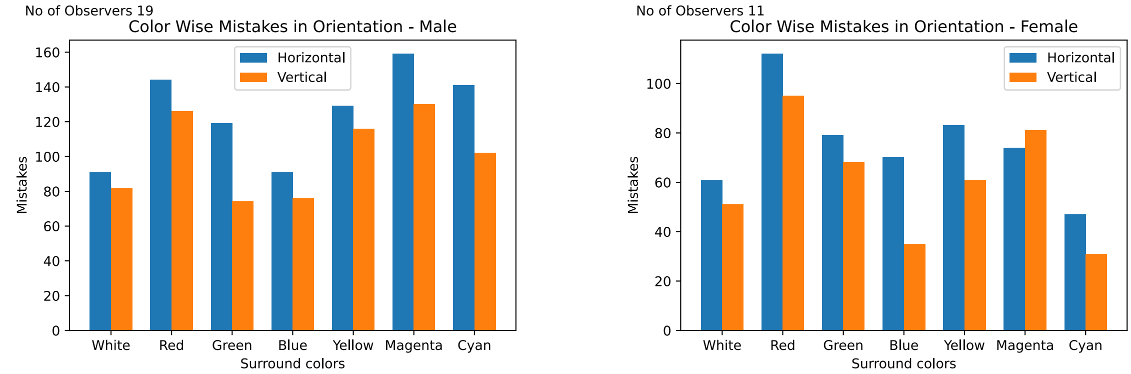


Figure 4.13: *Vertical and horizontal color wise mistakes done in the experiment.*

4.5.1 Gender based segregation

The color wise based vertical and horizontal mistakes were further segregated gender wise into two categories: males and females as depicted in Figure 4.14. It can be inferred from color and gender wise segregated results that they also provide an evidence that vertical visual acuity is better than horizontal. Moreover, males have done highest number of mistakes in magenta surround color, and lowest in blue and white surround color in comparison with all other surround colors used in experiment as shown in Figure 4.14(a). Where as, in the case of females, highest number of mistakes are done in red surround color and lowest number of mistakes in cyan surround color as shown in Figure 4.14(b). It is worth noticing that females have done more mistakes in vertical direction in magenta surround color than horizontal direction, which suggests that it is difficult to perceive gaps opening direction for both genders in magenta surround color than other surround colors.



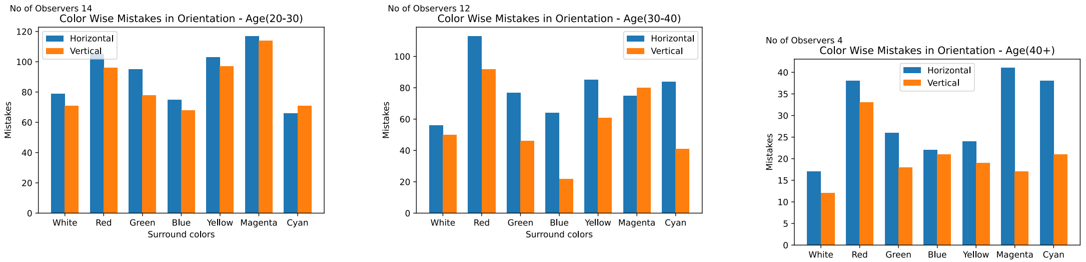
((a)) *Vertical and horizontal color wise mistakes done by male observers in the experiment.*

((b)) *Vertical and horizontal color wise mistakes done by females observers in the experiment.*

Figure 4.14: *Vertical and horizontal color wise mistakes done by all observers segregated by gender to show the gender wise dispersion of results. Number of males and females are shown in the top left of each graph.*

4.5.2 Age based segregation

The color wise based vertical and horizontal mistakes were further segregated in three age groups; a group of 14 young subjects, ranging from 20 (inclusive) to 30 (exclusive) years old as shown in Figure 4.15(a); a group of middle-aged subjects, ranging from 30 (inclusive) to 40 (exclusive) years old as shown in Figure 4.15(b); and a group of 4 elderly subjects, aged 40 years and above as shown in Figure 4.15(c). One notable observation regarding age and color-based visual representation is the consistent prevalence of horizontal direction based mistakes over vertical ones, as it has been previously mentioned, with few exceptions. One of exception is that, young observers exhibit slightly higher errors in the vertical direction compared to the horizontal direction when presented with a cyan surround color, as depicted in Figure 4.15(a). However, for other age groups, the horizontal errors are significantly higher than the vertical errors in the presence of a cyan surround color as depicted in Figure 4.15(b) and 4.15(c). This discrepancy can be attributed to the inconsistent performance of young observers during the experiment with a cyan surround color or the difficulty in perceiving gaps in stimuli under this particular surround color. In previous section 4.3 it was observed that older observers tend to spend more time processing stimuli with a cyan surround color, as evidenced by time based graphs in Figure 4.9, corroborating that it is difficult to perceive stimuli in cyan surround color. A similar pattern can also be observed in the middle aged observer group when exposed to a magenta surround color, where the frequency of vertical mistakes is slightly higher than that of horizontal mistakes. Furthermore, a general trend can be observed indicating that with the increasing of observers age, there is an increasing disparity between vertical and horizontal errors. This suggests that as individuals grow older, their horizontal direction based visual acuity deteriorates.



((a)) *color wise mistakes done by the observers with age between 20(included) to 30(excluded) years.*

((b)) *color wise mistakes done by the observers with age between 30(included) to 40(excluded) years.*

((c)) *color wise mistakes done by the observers with age between 40 years and above.*

Figure 4.15: *Vertical and horizontal color wise mistakes represented by bar plots segregated by age groups to show the age wise dispersion of the mistakes of observers. There are three age group, young, middle-age and elders. Number of observers are shown in the top left of each graph.*

5 Discussion

The aim of argument, or of discussion, should not be victory, but progress.

Jospeh Joubert

This study involved the implementation of a psychophysical experiment on a HDR display, with the objective of investigating the impact of luminance adaptation on luminance contrast. Modified Landolt C was used as stimulus in the experiment inspired by the work of Westheimer and McKee (1975), that demonstrated that good visual acuity does not necessarily require a stationary retinal image. The stimulus was presented on display at a visual angle of 2°, with the observer positioned 40 cm away from the display. A dark circular shape with a luminance of 0.03 cd/m^2 was employed within a visual angle of 10° on display as background. The experimental setup involved utilising the display's rest pixel area as a surrounding. The luminance contrast between the stimulus and background was held constant, while the luminance of the surround were manipulated along different hues and examined in this experiment. Furthermore, the Landolt C stimuli utilised in the experiment featured both vertical and horizontal openings, giving a hint about the difference in horizontal and vertical perception, based on the obtained results. Additionally, the influence of gender and age on contrast perception was also examined in the analysis of the results.

5.1 Subjective assessment outcomes

The primary outcome of the experiment was the determination of luminance thresholds for observers perception, specifically identifying the minimum luminance at which a certain contrast luminance becomes invisible to observers, to understand the phenomenon of luminance adaptation under different surround colors. It was found that luminance adaptation occurs in all surround colors, but degree of adaptation varied among all of them, especially in the red, green, blue, and yellow surround colors. The surround color red is indicative of the highest level of adaptation observed during the experiment, while yellow is representative of the lowest level of adaptation observed during the experiment. The observed outcomes appear to align with the conclusions drawn by High et al. (2023) in their study on the Helmholtz-Kohlrausch (H-K) effect, that the color yellow exhibits the lowest H-K effect, while the red hue demonstrates a relatively high H-K effect. Moreover, it was also found that, red surround color took highest number of stimuli to reach a threshold than other surround colors, and on average most time was spent on red surround color stimuli, suggesting the difficulty of perception under red surround color. It was found that on average least amount of time was spent on blue surround based stimuli, suggesting the ease of perception in blue surround color than other surround colors. Furthermore, this thesis has yielded additional outcomes indicating that HVS may possess superior perception in the vertical dimension compared to the horizontal dimension. However, it is important to note that these outcomes necessitate further investigation and verification. Drawing such definitive conclusions from a limited sample of observers would be challenging; number of observers in this experiment were only 30. And it was also found that with age the horizontal perception deteriorates. Furthermore, the findings indicate that luminance thresholds tend to increase with age among observers. However, this contradicts the expected trend, as visual acuity in the HVS typically decreases with age. Upon closer examination, it was discovered that the elder observers in the study were all professors who spent twice as much time on each stimulus compared to the younger observers. This extended exposure time may have allowed the elder observers to adapt more effectively. Moreover, elder observers, being professors, possessed a better understanding of HVS and color science compared to the average observers. This disparity in understanding may have introduced a bias into the results, as one elder observer reported that he was able to perceive contrast more effectively through the use of eye flickering.

5.2 Influence of color effects

Observers in the experiment reported experiencing certain color effects, which could potentially impact the obtained results. Some visual phenomena were observed in the experiment, including the afterimage effect, chromatic induction, mach bands, and the H-K effect. Exploring the entirety of color effects and effectively managing them fell beyond the scope of this research endeavour; however, a subset of these effects were addressed within the confines of this study. The afterimage effect was mitigated by implementing a 20-second interval between the hue shift of the surrounding. During the first 10 seconds of this interval, a blank screen was displayed on the monitor, which is also good for eye comfort. Subsequently, for the remaining 10 seconds, the luminance of the surrounding environment gradually increased to a fixed luminance level to facilitate the adaptation of the HVS to the new surround color. Although this approach did not completely eliminate the influence of the afterimage effect, it did significantly reduce its impact. Mach bands were observed at the edges of a background circle and were mitigated through the process of smoothing. However, this phenomenon did not significantly impact the results, as the focus of the experiment pertained to determining the direction of stimulus opening, which remained unaffected by the presence of Mach bands. The phenomenon of chromatic induction was noted by certain observers, who observed that the black background circle occasionally appeared to adopt the same color as the surrounding area. This color effect, resulting from the induction of chroma from the surrounding region, was not addressed within the scope of this study.

6 Conclusion

The more I learn, the more I realize how much I don't know.

Albert Einstein

A comprehensive psychophysical study was conducted in this experiment to understand the effect of luminance, out of 10° visual angle (surround) on luminance contrast in foveal view. The experiment employed multiple luminance scales of the surround, encompassing both achromatic color and chromatic colors such as red, green, blue, yellow, cyan, and magenta. The experiment involved a total of thirty participants who were tasked with recognizing the orientation of stimulus openings to determine the luminance threshold of their visual system in various surround colors using a threshold and matching method based psychophysical experiment, specifically focusing on luminance adaptation.

The experimental findings revealed the impact of surrounding color on the process of luminance adaptation and the extent of adaptation across various surround colors. The study revealed that the responses of both inter and intra observers exhibited higher levels of consistency when presented with a blue surround color, while demonstrating a notable lack of consistency when presented with a red surround color. The observed phenomenon can be attributed to either consistency or to the process of adaptation. Specifically, it indicates that the HVS experiences the least amount of luminance adaptation when exposed to a blue and yellow surround colors, while the highest level of adaptation occurs when exposed to a red surround color. The observers achieved the highest luminance thresholds when presented with green and cyan surround colors. This is because green and cyan surround colors are perceived to have the highest luminance after white and yellow. However, the perceived brightness in yellow is relatively low due to the low H-K effect, and the effect of color on perceived brightness in white is negligible, leading to lower thresholds of luminance in yellow and white when compared to green and cyan in experiment.

Additionally, it has been observed that chromatic surround colors exhibit greater luminance adaptation compared to achromatic surround color. This can be attributed, in part, to the absence of any color effect on perceived brightness in achromatic surround color. The study on chromatic surround colors revealed that red exhibits the highest level of luminance adaptation, while yellow demonstrates the lowest level of luminance adaptation. These findings align with the observations made in the H-K effect, as discussed by High et al. (2023) Ullah et al. (2022). Additionally, it was observed that the red surround color required the highest number of stimuli in the experiment to reach the threshold, whereas the blue and yellow surround colors required the least number of stimuli. Furthermore, it was observed that participants allocated a greater amount of time to stimuli presented with a red surround color, while dedicating the least amount of time to stimuli presented with a blue surround color. There exists a visible correlation whereby an increased duration of exposure to a particular color results in a corresponding enhancing of luminance adaptation within the HVS for that specific color. Additionally, it was observed that males exhibit higher luminance thresholds compared to females. It was observed that luminance thresholds increased with age, which appears to contradict the typical decrease in acuity associated with ageing. However, it was discovered that the older observers in the study were all professors who possessed a foundational understanding of color science and the HVS. This finding suggests that their responses may have been influenced by their expertise, as one older observer mentioned an ability to perceive contrast more effectively through eye flickering.

Moreover, a supplementary discovery emerged from this study, specifically pertaining to the perception of vertical and horizontal orientations. The experimental findings indicate that HVS demonstrates better perception in the vertical direction compared to the horizontal direction. Additionally, it was discovered that as individuals age, there is an increasing disparity between their visual acuity in both the vertical and horizontal directions. Younger observers exhibited nearly equivalent visual capabilities in both directions, whereas older individuals demonstrated a decline in horizontal vision. Furthermore, the study revealed that the greatest number of mistakes occurred in the presence of a red surround color, while the fewest errors were made in the presence of a blue surround color. This finding suggests that perceiving contrast in the presence of a red surround color was challenging, leading observers to spend more time in this condition. Consequently, this prolonged exposure to the red surround color ultimately resulted in observers reaching their highest thresholds in this particular condition.

6.1 Future work

This study produced significant findings regarding the impact of surround in luminance adaptation. However, there are still several areas that need further investigation in order to deepen our understanding of the intricate phenomena of HVS, specially luminance adaptation. Several potential directions can be derived from the findings of this study, few of them are mentioned below.

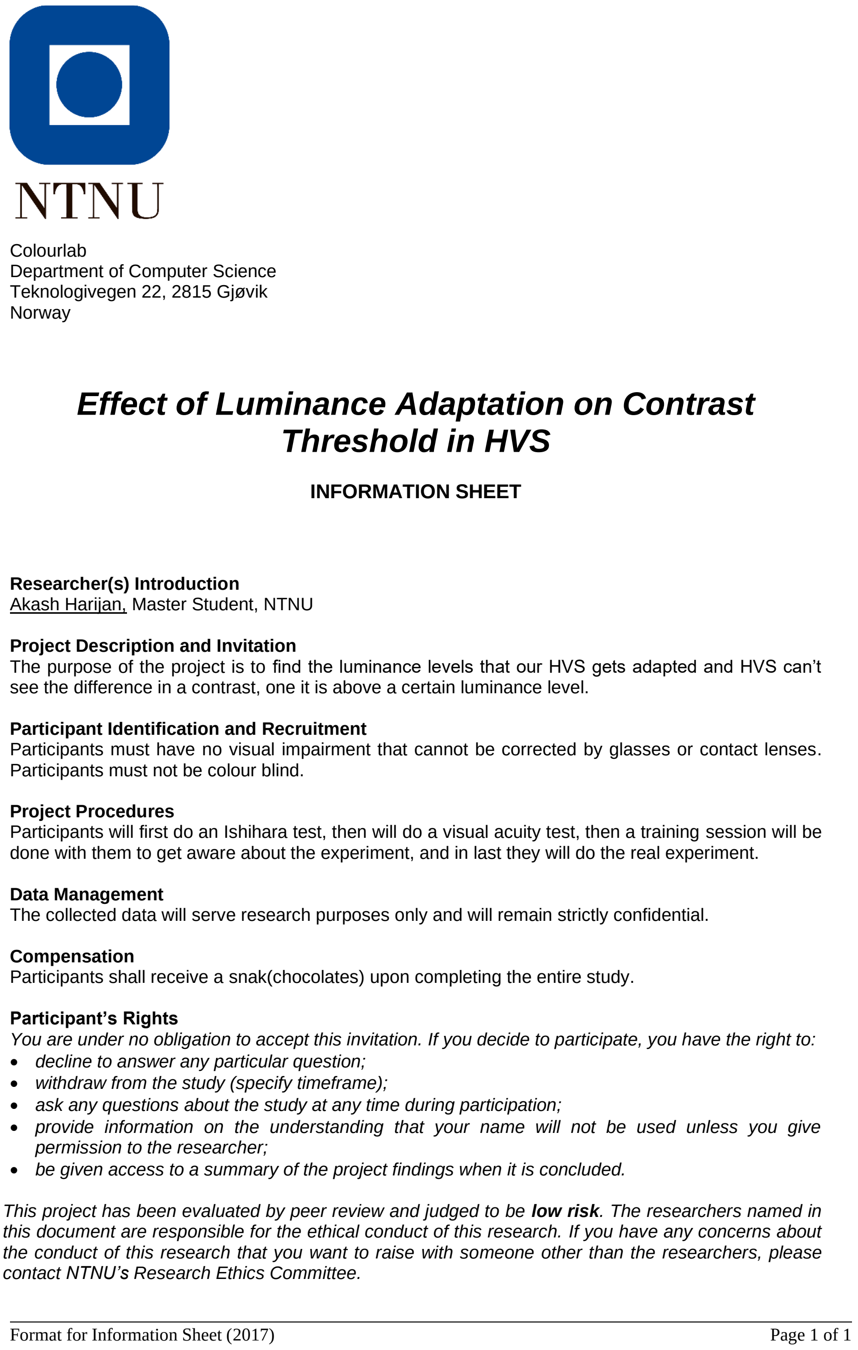
1. **Model**: An attempt can be made to develop a statistical or machine learning model that accurately represents the acquired data from the experiment. This model aims to comprehend the behaviour of HVS under various surround conditions, which were not included in the experiment. The objective is to determine whether the obtained data is sufficiently reliable to establish a comprehensive model for luminance adaptation.

2. **color appearance model**: Incorporating the discoveries of this study into future color appearance models, and identifying the limitations of existing color appearance models through a comparative analysis of their outcomes with the model derived from the findings of this research, as outlined in the initial point.

3. **color effects**: The present study revealed that the outcomes were subject to the influence of certain color effects. Further investigation is needed to gain a comprehensive understanding of the impact of these color effects on both overall luminance adaptation and specifically on luminance adaptation by foveal surrounding.

A | Appendix

In this section, information sheet as depicted in Figure A.1 presented to each observer before asking them sign a consent form as depicted in Figure A.2 to give consent of their data being used in this experiment.



NTNU

Colourlab
Department of Computer Science
Teknologivegen 22, 2815 Gjøvik
Norway

Effect of Luminance Adaptation on Contrast Threshold in HVS

INFORMATION SHEET

Researcher(s) Introduction
Akash Harijan, Master Student, NTNU

Project Description and Invitation
The purpose of the project is to find the luminance levels that our HVS gets adapted and HVS can't see the difference in a contrast, one it is above a certain luminance level.

Participant Identification and Recruitment
Participants must have no visual impairment that cannot be corrected by glasses or contact lenses. Participants must not be colour blind.

Project Procedures
Participants will first do an Ishihara test, then will do a visual acuity test, then a training session will be done with them to get aware about the experiment, and in last they will do the real experiment.

Data Management
The collected data will serve research purposes only and will remain strictly confidential.

Compensation
Participants shall receive a snak(chocolates) upon completing the entire study.

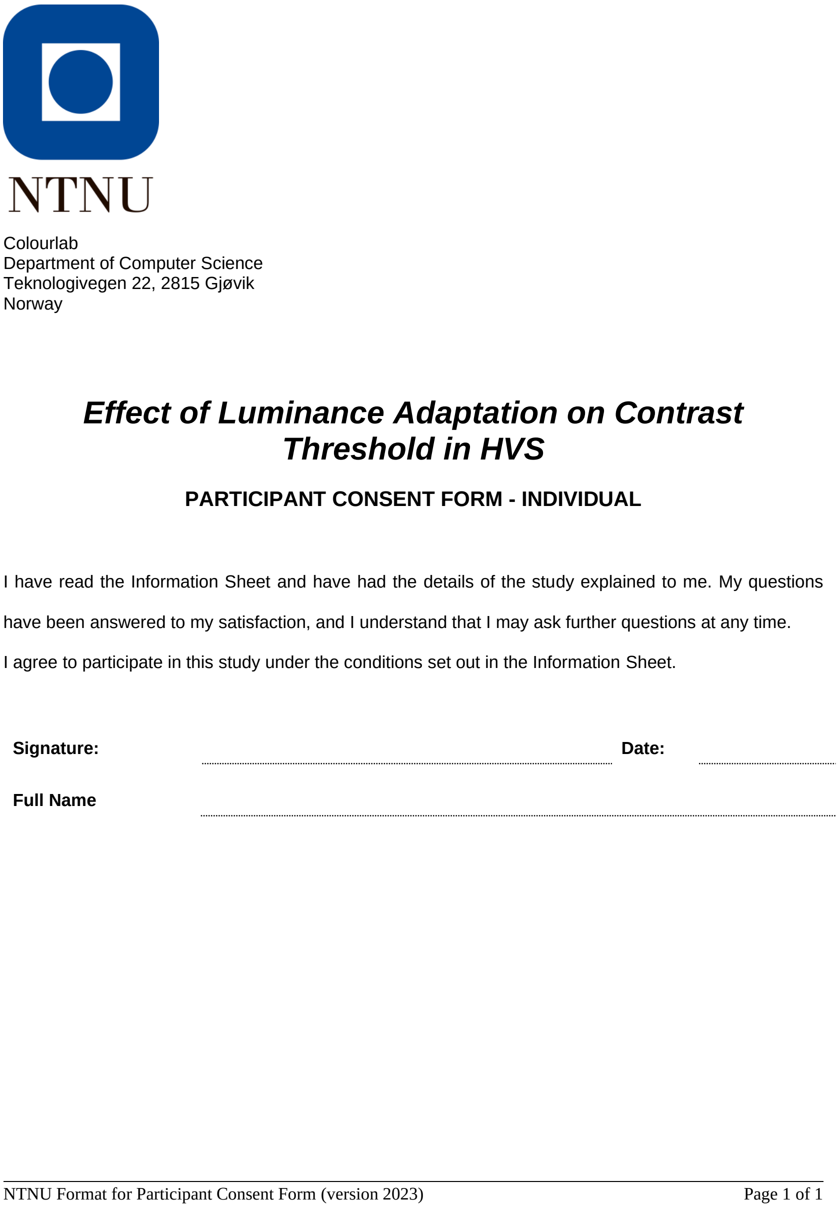
Participant's Rights
You are under no obligation to accept this invitation. If you decide to participate, you have the right to:

- *decline to answer any particular question;*
- *withdraw from the study (specify timeframe);*
- *ask any questions about the study at any time during participation;*
- *provide information on the understanding that your name will not be used unless you give permission to the researcher;*
- *be given access to a summary of the project findings when it is concluded.*

This project has been evaluated by peer review and judged to be ***low risk****. The researchers named in this document are responsible for the ethical conduct of this research. If you have any concerns about the conduct of this research that you want to raise with someone other than the researchers, please contact NTNU's Research Ethics Committee.*

Format for Information Sheet (2017) Page 1 of 1

Figure A.1: *Information sheet presented to observers before asking them to sign the consent form.*



Colourlab
Department of Computer Science
Teknologivegen 22, 2815 Gjøvik
Norway

Effect of Luminance Adaptation on Contrast Threshold in HVS

PARTICIPANT CONSENT FORM - INDIVIDUAL

I have read the Information Sheet and have had the details of the study explained to me. My questions have been answered to my satisfaction, and I understand that I may ask further questions at any time.

I agree to participate in this study under the conditions set out in the Information Sheet.

Signature: .... **Date:** ....

Full Name ....

NTNU Format for Participant Consent Form (version 2023) Page 1 of 1

Figure A.2: *Consent form used to get consent from observers.*

Bibliography

(2023). Eizo coloredge cg3146. `https://www.eizoglobal.com/products/coloredge/cg3146/`. [Accessed June 6, 2023]. (cited on pages 27, 28, and 29)

(2023). Psychtoolbox. `http://psychtoolbox.org/`. [Accessed June 6, 2023]. (cited on page 27)

Adelson, E. H. and Jonides, J. (1980). The psychophysics of iconic storage. *Journal of Experimental Psychology: Human Perception and Performance*, 6(3):486. (cited on page 2)

Akyüz, A. O. and Reinhard, E. (2006). Color appearance in high-dynamic-range imaging. *Journal of Electronic Imaging*, 15(3):033001–033001. (cited on page 3)

Atchison, D. (2023). *Optics of the human eye*. CRC Press. (cited on page 11)

Barten, P. G. (1992). Physical model for the contrast sensitivity of the human eye. In *Human Vision, Visual Processing, and Digital Display III*, volume 1666, pages 57–72. SPIE. (cited on page 20)

Barten, P. G. (1999). *Contrast sensitivity of the human eye and its effects on image quality*. SPIE press. (cited on page 19)

Barten, P. G. (2003). Formula for the contrast sensitivity of the human eye. In *Image Quality and System Performance*, volume 5294, pages 231–238. SPIE. (cited on page 20)

Campbell, F. W. and Maffei, L. (1974). Contrast and spatial frequency. *Scientific American*, 231(5):106–115. (cited on page 20)

Chen, A.-H., Zhou, Y., Gong, H.-Q., and Liang, P.-J. (2005). Luminance adaptation increased the contrast sensitivity of retinal ganglion cells. *Neuroreport*, 16(4):371–375. (cited on page 2)

Clark, J. (1924). The ishihara test for color blindness. *American Journal of Physiological Optics*. (cited on page 43)

Daly, S., Kunkel, T., Sun, X., Farrell, S., and Crum, P. (2013). 41.1: Distinguished paper: Viewer preferences for shadow, diffuse, specular, and emissive luminance limits of high dynamic range displays. In *SID Symposium Digest of Technical Papers*, volume 44, pages 563–566. Wiley Online Library. (cited on page 13)

Deter, C. and Biehlig, W. (2004). Scanning laser projection display and the possibilities of an extended color space. In *Conference on Colour in Graphics, Imaging, and Vision*, volume 2004, pages 531–535. Society for Imaging Science and Technology. (cited on page 14)

DiCarlo, J. M. and Wandell, B. A. (2000). Rendering high dynamic range images. In *Sensors and Camera Systems for Scientific, Industrial, and Digital Photography Applications*, volume 3965, pages 392–401. SPIE. (cited on page 9)

DisplayHDR (2023). DisplayHDR - delivering high dynamic range (hdr) and wide color gamut (wcg) to the display industry. `https://displayhdr.org/guide/`. [Accessed June 6, 2023]. (cited on page 30)

EIZO Corporation ([2019]). ColorNavigator 7. Software. Version [Version number]. (cited on page 34)

Fairchild, M. D. (2013). *Color appearance models*. John Wiley & Sons. (cited on pages 21, 40, 49, and 63)

Fang, J., Xu, H., Lv, W., and Luo, M. R. (2016). 59-3: Proper luminance of hdr tv system. In *SID symposium digest of technical papers*, volume 47, pages 806–808. Wiley Online Library. (cited on page 23)

Foster, D. H. (2011). Color constancy. *Vision research*, 51(7):674–700. (cited on page 3)

High, G., Green, P., and Nussbaum, P. (2023). The helmholtz-kohlrausch effect on display-based light colors and simulated substrate colors. *Color Research & Application*, 48(2):167–177. (cited on pages 54, 55, 70, and 74)

Hoefflinger, B. (2007). *High-dynamic-range (HDR) vision*. Springer. (cited on page 14)

in Colour, C. (accessed 2023). Cameras vs. the human eye. `https://www.cambridgeincolour.com/tutorials/cameras-vs-human-eye.htm`. (cited on pages 10 and 89)

Kelly, D. (1974). Spatio-temporal frequency characteristics of color-vision mechanisms. *JOSA*, 64(7):983–990. (cited on page 38)

Kelly, D. (1977). Visual contrast sensitivity. *Optica Acta: International Journal of Optics*, 24(2):107–129. (cited on pages 3, 4, 19, 38, and 89)

Kelly, D. and Savoie, R. (1973). A study of sine-wave contrast sensitivity by two psychophysical methods. *Perception & Psychophysics*, 14(2):313–318. (cited on page 45)

King-Smith, P. E. and Carden, D. (1976). Luminance and opponent-color contributions to visual detection and adaptation and to temporal and spatial integration. *JOSA*, 66(7):709–717. (cited on page 2)

Konica Minolta (2023). CS-2000A/CS-2000 Spectroradiometer. `https://www.konicaminolta.eu/eu-en/hardware/measuring-instruments/light-and-display-measurement/spectroradiometer/cs-2000a-cs-2000`. [Accessed June 6, 2023]. (cited on page 36)

Krauskopf, J. (1980). Discrimination and detection of changes in luminance. *Vision research*, 20(8):671–677. (cited on page 2)

Kuang, J., Johnson, G. M., and Fairchild, M. D. (2007). icam06: A refined image appearance model for hdr image rendering. *Journal of Visual Communication and Image Representation*, 18(5):406–414. (cited on page 3)

Kunkel, T. and Reinhard, E. (2010). A reassessment of the simultaneous dynamic range of the human visual system. In *Proceedings of the 7th Symposium on Applied Perception in Graphics and Visualization*, pages 17–24. (cited on page 22)

Lai, S. and Lowrey, T. (2008). Ieee int. electron devices meeting. (cited on page 11)

Langendijk, E. H. and Hammer, M. (2010). 14.4: Contrast requirements for oleds and lcds based on human eye glare. In *SID Symposium Digest of Technical Papers*, volume 41, pages 192–194. Wiley Online Library. (cited on page 13)

Laughlin, S. B. (1989). The role of sensory adaptation in the retina. *Journal of Experimental Biology*, 146(1):39–62. (cited on page 4)

Ledda, P., Santos, L. P., and Chalmers, A. (2004). A local model of eye adaptation for high dynamic range images. In *Proceedings of the 3rd international conference on Computer graphics, virtual reality, visualisation and interaction in Africa*, pages 151–160. (cited on pages 2 and 22)

Lee, E., Kim, S., Park, H., Bae, J., Lee, S., and Kim, H. (2012). A study on the ergonomic aspects of the proper luminance level of displays. *Journal of Information Display*, 13(4):159–166. (cited on page 23)

Lee, G. J., Choi, C., Kim, D.-H., and Song, Y. M. (2018). Bioinspired artificial eyes: optic components, digital cameras, and visual prostheses. *Advanced Functional Materials*, 28(24):1705202. (cited on page 11)

Liu, Y., Zhu, Y., and Luo, M. R. (2022). A model to predict visual comfort for mobile displays. *Color Research & Application*, 47(6):1229–1241. (cited on page 24)

Loomis, J. M. and Berger, T. (1979). Effects of chromatic adaptation on color discrimination and color appearance. *Vision Research*, 19(8):891–901. (cited on page 2)

Mantiuk, R., Daly, S. J., Myszkowski, K., and Seidel, H.-P. (2005). Predicting visible differences in high dynamic range images: model and its calibration. In *Human Vision and Electronic Imaging X*, volume 5666, pages 204–214. SPIE. (cited on page 20)

Mantiuk, R., Krawczyk, G., Myszkowski, K., and Seidel, H.-P. (2004). Perception-motivated high dynamic range video encoding. *ACM Transactions on Graphics (TOG)*, 23(3):733–741. (cited on pages 2 and 20)

Mantiuk, R., Krawczyk, G., Zdrojewska, D., Mantiuk, R., Myszkowski, K., and Seidel, H.-P. (2015). *High dynamic range imaging*. na. (cited on pages 9, 10, 11, 12, 13, 14, 16, 20, and 93)

Mark, D. (2005). Fairchild color appearance models-wiley-is&t series in imaging science and technologies. (cited on page 18)

Matsumoto, T., Haga, S., Nakatsue, T., Kubota, S., Kubota, Y., Imabayashi, K., Kishimoto, K., Goshi, S., Imai, S., and Igarashi, Y. (2011). 18.2: Distinguished paper: Appropriate luminance of lcd-tv screens under actual viewing conditions at home. In *SID Symposium Digest of Technical Papers*, volume 42, pages 221–224. Wiley Online Library. (cited on page 22)

McCann, J. J. and Rizzi, A. (2007a). Camera and visual veiling glare in hdr images. *Journal of the Society for Information Display*, 15(9):721–730. (cited on page 13)

McCann, J. J. and Rizzi, A. (2007b). Veiling glare: the dynamic range limit of hdr images. In *Human Vision and Electronic Imaging XII*, volume 6492, pages 394–403. SPIE. (cited on page 13)

Moroney, N., Fairchild, M., Hunt, R., and Li, C. (2002). The ciecam02 color appearance model. (cited on page 3)

Murdoch, M. (2013). Human-centered display design: balancing technology & perception. (cited on pages 16, 17, 18, 19, and 89)

Myszkowski, K., Mantiuk, R., and Krawczyk, G. (2008). High dynamic range video. synthesis digital library of engineering and computer science. *Morgan & Claypool Publishers, San Rafael, USA.* (cited on pages 10 and 93)

Pattanaik, S. N., Tumblin, J., Yee, H., and Greenberg, D. P. (2000). Time-dependent visual adaptation for fast realistic image display. In *Proceedings of the 27th annual conference on Computer graphics and interactive techniques*, pages 47–54. (cited on page 22)

Phung, T. H., Kong, X., Leloup, F. B., Smet, K. A., and Hanselaer, P. (2022). Brightness appearance of self-luminous stimuli on a non-uniform background. *Color Research & Application*, 47(6):1330–1344. (cited on pages 5 and 25)

Pollen, D. A. and Ronner, S. F. (1983). Visual cortical neurons as localized spatial frequency filters. *IEEE Transactions on Systems, Man, and Cybernetics*, (5):907–916. (cited on page 20)

Poot, L. (2000). Light adaptation and early processing in the human visual system. (cited on pages 1, 2, and 3)

Posch, C., Serrano-Gotarredona, T., Linares-Barranco, B., and Delbruck, T. (2014). Retinomorphic event-based vision sensors: bioinspired cameras with spiking output. *Proceedings of the IEEE*, 102(10):1470–1484. (cited on page 11)

Poynton, C. A. (1996). *A technical introduction to digital video.* John Wiley & Sons, Inc. (cited on page 16)

Reinhard, E., Heidrich, W., Debevec, P., Pattanaik, S., Ward, G., and Myszkowski, K. (2010). *High dynamic range imaging: acquisition, display, and image-based lighting.* Morgan Kaufmann. (cited on pages 13 and 15)

Reinhard, E., Khan, E. A., Akyuz, A. O., and Johnson, G. (2008). *Color imaging: fundamentals and applications.* CRC Press. (cited on pages 15, 16, and 89)

Seetzen, H., Heidrich, W., Stuerzlinger, W., Ward, G., Whitehead, L., Trentacoste, M., Ghosh, A., and Vorozcovs, A. (2004). High dynamic range display systems. In *ACM SIGGRAPH 2004 Papers*, pages 760–768. (cited on page 9)

Seetzen, H., Li, H., Ye, L., Heidrich, W., Whitehead, L., and Ward, G. (2006). 25.3: Observations of luminance, contrast and amplitude resolution of displays. In *SID Symposium Digest of Technical Papers*, volume 37, pages 1229–1233. Wiley Online Library. (cited on page 14)

Shapley, R. and Enroth-Cugell, C. (1984). Visual adaptation and retinal gain controls. *Progress in retinal research*, 3:263–346. (cited on pages 1 and 4)

Sloane, M. E., Owsley, C., and Jackson, C. A. (1988). Aging and luminance-adaptation effects on spatial contrast sensitivity. *JOSA A*, 5(12):2181–2190. (cited on page 2)

Spillmann, L. and Conlon, J. E. (1972). Photochromatic interval during dark adaptation and as a function of background luminance. *JOSA*, 62(2):182–185. (cited on page 2)

Sun, P.-L., Li, H.-C., and Ronnier Luo, M. (2017). Background luminance and subtense affects color appearance. *Color Research & Application*, 42(4):440–449. (cited on pages 3 and 24)

Ullah, E., High, G. P., and Green, P. J. (2022). Quantifying and evaluating colour appearance models based on helmholtz kohlrausch effect. In *Proceedings of the International Colour Association (AIC) Conference 2022*. The International Colour Association. (cited on pages 51 and 74)

Van Ngo, K., Dokkeberg, C. A., Farup, I., Pedersen, M., et al. (2015). Quickeval: a web application for psychometric scaling experiments. In *Image Quality and System Performance XII*, volume 9396, pages 212–224. SPIE. (cited on page 44)

Vibhoothi, V., Katsenou, A., Squires, J., Pitie, F., and Kokaram, A. (2023). Recommendations for verifying hdr subjective testing workflows. In *2023 15th International Conference on Quality of Multimedia Experience (QoMEX)*. (cited on page 30)

Wandell, B. A. (1995). *Foundations of vision.* sinauer Associates. (cited on pages 14 and 16)

Ward, G. (2008). 59.2: Defining dynamic range. In *SID Symposium Digest of Technical Papers*, volume 39, pages 900–902. Wiley Online Library. (cited on page 13)

Watson, A. B. and Pelli, D. G. (1983). Quest: A bayesian adaptive psychometric method. *Perception & psychophysics*, 33(2):113–120. (cited on page 45)

Weisstein, N. (1970). Neural symbolic activity: a psychophysical measure. *Science*, 168(3938):1489–1491. (cited on page 2)

Werblin, F. (1971). Adaptation in a vertebrate retina: intracellular recording in necturus. *Journal of Neurophysiology*, 34(2):228–241. (cited on page 2)

Westheimer, G. and McKee, S. P. (1975). Visual acuity in the presence of retinal-image motion. *JOSA*, 65(7):847–850. (cited on pages 39 and 69)

Williams, D., Hofer, H., Carroll, J., Neitz, M., and Neitz, J. (2003). Organization of the human trichromatic cone mosaic. *Investigative Ophthalmology & Visual Science*, 44(13):1909–1909. (cited on page 18)

Wüller, D. and Gabele, H. (2007). The usage of digital cameras as luminance meters. In *Digital Photography III*, volume 6502, pages 281–291. SPIE. (cited on page 13)

Wyszecki, G. and Stiles, W. S. (2000). *Color science: concepts and methods, quantitative data and formulae*, volume 40. John wiley & sons. (cited on page 49)

X-Rite (2023). i1Profiler. `https://www.xrite.com/categories/formulation-and-quality-assurance-software/i1profiler`. [Accessed June 6, 2023]. (cited on pages 34 and 35)

XRite (2023). i1Display Pro. `https://www.xrite.com/categories/calibration-profiling/i1display-pro`. [Accessed June 6, 2023]. (cited on page 34)

Yamaguchi, H. and Fairchild, M. (2004). A study of simultaneous lightness perception for stimuli with multiple illumination levels. In *Color and Imaging Conference*, volume 2004, pages 22–28. Society for Imaging Science and Technology. (cited on page 3)

Yoshida, A., Mantiuk, R., Myszkowski, K., and Seidel, H.-P. (2006). Analysis of reproducing real-world appearance on displays of varying dynamic range. In *Computer Graphics Forum*, volume 25, pages 415–426. Wiley Online Library. (cited on page 13)

List of Figures

List of Tables