Perception of a 3D Colored Stereo Image from One Colored and One Gray-Scale Images

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Dedication

This work is dedicated in loving memory to my mother Anny.

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Abstract

Stereoscopic vision is one of the most interesting tasks used in daily life. It facilitates depth perception used in order to safely navigate in our three–dimensional (3D) world to self-orient in space, and to visually recognize objects. Color vision supplies us with important additional information.

The percept generated by the human visual system is far more complex than the sum of the two images seen by both eyes. It is well known that depth perception can be obtained by viewing a stereo pair that was acquired from slightly different angles of view through a stereoscope. A stereo pair consisting of two monochromatic (gray-scale) images yields a monochromatic 3D image and a stereo pair consisting of two color images fused into a colorful 3D image. Computer vision systems and remote controlled teleoperation systems use algorithms that combines color and depth. Both features are important for obstacle and target detection and benefits are gained from combining both.

When both eyes are presented with dissimilar stimuli the visual system is "confused" and does not always manage to fuse them into a single stable percept. This unstable phenomenon is called *binocular rivalry*. Previous works have involved images with different features being presented to the two eyes: Contrast, different content (house vs. face), different line direction, two different colors, etc.

However, a number of questions were left open: What if one of the color images within a color stereo pair is replaced by a gray-scale image? Will depth perception remain intact even though chromatic data is absent from one of the stereo images pairs? Will color perception still be valid? This thesis addresses these open questions.

Controlled psychophysical experiments validated the hypothesis that a stereo pair consisting of one gray-scale image and one color image (will be referred to as MIX) produces 3D color perception. Four basic combinations were presented to each subject: 1) Full color stereo pair (color image on both sides); 2) Full monochromatic pair (gray-scale image on both sides); 3) Two MIX stereo pair (color image on the right side and a gray-scale image on the left side and vice versa). Various image sets were presented to the subjects with two apparatus: A stereoscope an HMD (Head Mounted Display). All subjects perceived a colored image with depth. No degradation in depth perception was measured, although some degradation in the perception of color was observed.

It is already known that the two images in a stereo pair are not required to have equal sharpness in order to perceive depth. A certain amount of blur on one of the images within a gray-scale pair or color pair will not affect the depth perception obtained from both images. We have found that when the gray-scale image is blurred, depth perception remains nearly the same while color perception improves.

An effect of color perception asymmetry while viewing the MIX stereo pair was found. The interposition of the color image within the stereo pair (right or left image) influenced the color perception. Most subjects reported that when color image was presented to the right eye, color perception was better then when the color image was presented to the left eye.

We further investigated adding rivalrous patterns of diagonal lines (inclined +45 degrees on one image and -45 degrees on the other image) to both images of the MIX pair. While the direction of the line was altered, depth and color perception was stable. Additional experiments were conducted with various compression techniques applied to the gray-scale image. Results have shown that the basic effect can endure compression of various sorts.

Utilizing the findings reported in this study will allow for the perception of color and depth while at the same time reducing the number of channels needed to be transmitted or stored from six channels to only four channels. In addition, when additional compression is applied to the gray-scale image, the amount of data can be further reduced. The research presented explores the minimal requirements necessary for viewing a stereoscopic color image, from a psychophysical aspect. These findings may be relevant for solving various computer vision tasks like bandwidth reduction and efficient storage of color stereoscopic images.

Chapter 1

Introduction

Vision science is an interdisciplinary field of research. It combines physics, computer science, signal processing, neurobiology and psychology. It spans a broad band of research questions, from the color recognition mechanisms in the brain to the design and use of virtual reality and 3D apparatus. Human depth perception, binocular rivalry and color perception have been investigated for centuries.

What one perceives visually is not an exact translation of the image received at the retina. The eye provides abundant information about the surrounding world and yet, a small part of it is being processed. I believe that understanding the way we visually perceive the world is critically important in order to develop efficient vision algorithms and vision systems.

It is well known that depth perception can be obtained by viewing a stereo pair that was acquired from slightly different angles of view through a stereoscope. A stereo pair consisting of two monochromatic (gray-scale[1]) images yields a monochromatic 3D image and a stereo pair consisting of two color images fused into a colorful 3D image. Computer vision systems and remote controlled teleoperation systems use algorithms that combines color and depth. Both features are important for obstacle and target detection and benefits are gained from combining both.

When both eyes are presented with dissimilar stimuli the visual system is "confused" and does not always manage to fuse them into a single stable percept. This unstable phenomenon is called binocular rivalry. Previous works have involved images with different features being presented to the two eyes: Contrast, different content (house vs. face), different line direction and two different colors.

However, a number of questions were left open: What if one of the color images within a color stereo pair is replaced by a gray-scale image? Will depth perception remain intact even though chromatic data is absent from one of the stereo images pairs? Will color perception still be valid? This thesis addresses these open questions.

First, we study the color and depth perception in stereoscopic images formed by one color and one gray-scale images (referred to as MIX stereo image). When MIX images were viewed dichoptically, (different monocular stimuli imaged separately to the left and right eyes) fusion occurs and a 3D color image is seen. The key observation, is that although the color contents are radically different between the eyes

[1]In this dissertation, the terms monochromatic and gray-scale are synonymous.

(color versus monochrome) the color image dominating, producing a color percept.

During the experiments, the question of symmetry in the color perception of MIX stereo pairs was investigated. Since the MIX image is composed from one gray-scale and one colored image, two MIX combinations are possible. The first is color, presented to the right eye, and the gray-scale presented to the left eye (is referred to as BW-Col) and the second option is a color image that is presented to the left eye and a gray-scale image presented to the right eye (is referred to as Col-BW). The observers' reports of color perception seem to be affected by the eye to which the color image is presented.

Psychophysical experiments were conducted in order to validate the hypothesis of the existence of color asymmetry. The questions whether the color perception of a MIX stereo pair is asymmetric between the two eyes and how this asymmetry relates to the "classical" definition of a dominant eye and dominant hand were examined. Validation of this color asymmetry while viewing MIX stereo means that there is a difference in the perception of color between the two eyes that depends solely on which eye is viewing the color image. We further examine the questions of whether the dominant eye has any influence on fusion ability depth or color perception in tasks involving chromatic asymmetry between the two eyes. A majority of the observers, preferred one eye when viewing a MIX stereo pair. Color perception scores were significantly higher when the color image was presented to the observer preferred eye.

We further study the effects of blur on the depth and color perception of the MIX image. Blurred MIX stereo pairs were presented to subjects in order to investigate whether fusion, rivalry (a bi-stable perception phenomenon) or suppression occurs. The blur was introduced to one or both of the images in the MIX stereo pair by applying an averaging filter with a kernel of 3X3 or 5X5 to the image. Depth and color perception were investigated. Results show, that when blur is applied to one side of the stereo pair it merely causes a minor degradation in depth perception, in comparison to blur applied to both sides. Moreover, results have shown that color perception improves when the gray-scale image was blurred. These results imply that the amount of blur applied to the gray-scale image increases the predominance of the color image over the gray-scale one, and that a reduced amount of data can be used to represent the gray-scale image with minimal influence on stereoscopic impression. As expected, when the color image is blurred, color perception deteriorates. These findings are the basis for further investigation on the subject of compression.

The research described in this dissertation explores a phenomenon that can potentially be used as a basis for a color stereo compression method which is motivated by the properties of the Human Visual System (HVS). Several experiments were conducted for evaluating color and depth perception when the gray-scale image within the MIX pairs was further compressed. Data compression through quantization reduces the number of bits in the gray-scale image within the MIX image. A reduced representation using Gaussian Pyramid was also proven to be an effective representation of the gray-scale image and yet it does not reduce depth or color quality. Compressing the gray-scale image by means of a Gaussian Pyramid has demonstrated that a reduced image (in size and quality) can be transmitted with a color image as a MIX stereo pair with the expand operator performed on the receiver end.

Although transmission volume is reduced, depth and color perception is maintained. The same results stand when the gray-scale image is blurred.

The results have shown that further compression can be achieved by compressing the gray-scale image by various means, without impairing image perception. A number of compression approaches, which were tried, yield equivalent results concerning color and depth perception scoring, to those of blurring.

Next, form rivalry forced on the MIX stereo pair was examined. Rivalry is a bi-stable perception phenomenon associated with viewing two competing stimuli. When two dissimilar images are viewed separately through the two eyes, the perceived image may alternate in an unstable mode between the two stimuli. This fluctuation in perception is the phenomenon termed *binocular rivalry* or *retinal rivalry.*

Rivalry can be triggered by a variety of stimulus differences between the left and the right eye. The stimuli can differ in content (face vs. a house), color (red vs. green), contrast, contrast polarity, form, luminance, size or motion velocity [11]. In order to examine whether form rivalry will influence the color and depth perception of a MIX stereo pair, we elicited perceptual rivalry using a rivalrous pattern that was added to the MIX stereo pair, in the form of a diagonal grating. Since rivalry was not the outcome of mere chromatic differences, as was found before, the grating patches differed in orientation alone between the left and right images. Results show little or no effect of the existence of form rivalry on depth and color perception. Color is stable and clearly perceptible although rivalry exists and perception of the lines' direction alternated. No association was found between the direction of the lines and the color position within the stereo pair.

Utilizing the findings reported in this study will allow the perception of color and depth while reducing the number of channels needed to be transmitted or stored from six channels to only four channels. In addition, compression if added to the gray-scale image can further decrease the amount of data. The research presented explores the minimal requirements necessary for viewing a stereoscopic color image, from a psychophysical aspect. These finding might be relevant to solving various computer vision tasks like bandwidth reduction and an efficient storage of color stereoscopic images.

The dissertation is organized in the following way: Chapter 2)contains the background and related work concerning the visual pathway, color perception, depth perception, stereopsis, rivalry and compression. Chapter 3 describes the methods, procedures and apparatus used in the experiments. The rest of the dissertation is organized in chapters each dealing with a different research topic. Chapter 4 confirms the main hypothesis, that a pair of MIX images, constructed of one gray-scale and one color image, enables human perception of a three dimensional color image. Chapter 5 investigates color asymmetry in the presentation of MIX stereo pairs. Chapter 6 studies the way blur of the MIX image affects depth and color perception and whether there is a difference while blurring color or gray-scale images. Chapter 7 examines the influence of compression of gray-scale image within the MIX pair on color and depth perception. Chapter 8 examines whether form rivalry influences the color and depth perception of a MIX stereo pair. The last two chapters discuss future work and conclusions.

It may be possible for the reader to experience the phenomenon investigated in this dissertation using a limited free-viewing example (without the use of glasses). Reader capable of free-fusion can experience the MIX representation presented in Appendix A.

Chapter 2

Background

2.1 The Human Visual System

A brief overview of the human visual system is presented, concentrating on color vision, binocular vision and depth perception. A general overview on the role of the eye and brain in the visual pathway is presented. Color vision and stereo vision in their physical, physiological and psychophysical aspects are discussed. In addition, an overview on the ways humans utilize the properties of the visual system for an efficient image presentation and image compression is supplied.

2.1.1 Eye and brain – The visual pathway

The visual pathway is the tract of visual information flow leading from the eyes to the brain. It consists of the retina - located at the back of the eye, the LGN (Lateral Geniculate Nucleus), and the visual cortex. Figure 2.1,(taken from [34]) shows the eye and its three retinal layers. The information flows from the photoreceptors to the ganglion cells and then to the brain.

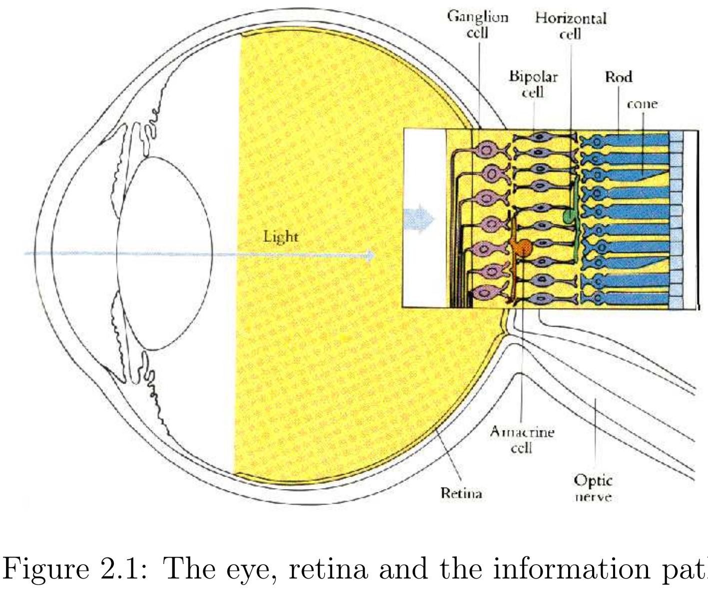


Figure 2.1: The eye, retina and the information path

The study of vision deals with the way we interact, perceive and respond to our environment. The process starts with the outside 3D world. Light reflected from objects is encoded by two separate sensors (the two eyes) into patterns. It is then translated into an electrical signal, compressed and transferred to the brain for further processing. The vision process gives us the representation of the outside world; however, this representation is not a fully detailed one. For example, we see colors in detail only in the center of the retina, the fovea, which occupies only five degrees of the visual field [2], but still perceive the entire image as colored. Another example is that we use our two horizontally separated eyes, acquire two slightly different images and still gain one single percept of the world (this phenomenon is referred to as singleness of vision). Moreover, the human eye's retina consists of about 120 million photoreceptors (rods and cones) that convert the image into electrical signals. All visual information is conveyed to the brain through approximately one million optic nerve fibers [2], which means that there is a considerable degree of compression (120:1) on the part of the visual path from the photoreceptors (located in the retina) to the ganglion cells that send the information to the brain via the optic nerve. To summarize, our perception is not an exact duplicate of the real world. It is much more complicated than the initial information encoded by the photoreceptors.

2.1.2 Left and right in the visual pathway

The term ***visual field*** refers to the portion of the outside world scene, that is seen by our two eyes. The *right visual field* refers to all the points placed on the right side of the visual field and the *left visual field* refers to all the points placed on the left side of the visual field. Figure 2.2 illustrates the right and left visual fields.

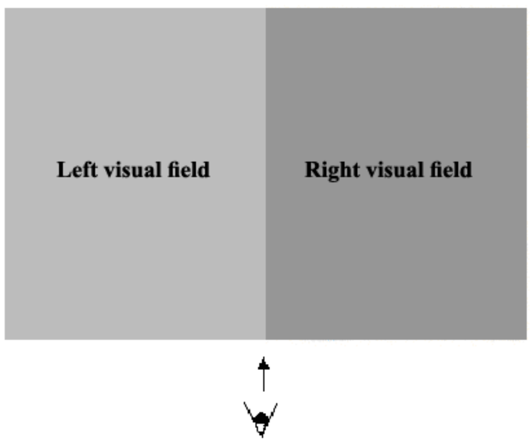


Figure 2.2: Right and left visual field.

Because the retinal images are reversed by the lenses, light coming from anywhere in the right half of the visual environment projects onto the two left half-retinas, and the information is sent to the left hemisphere. As can be seen in Figure 2.3 (modified from [34]), optic-nerve fibers from the left half of the left retina go to the hemisphere on the same side, whereas optic-nerve fibers from the left half of the right retina cross at the optic chiasm and arrive at the opposite hemisphere. Similarly, the output of the two right half-retinas end up in the right hemisphere [34].

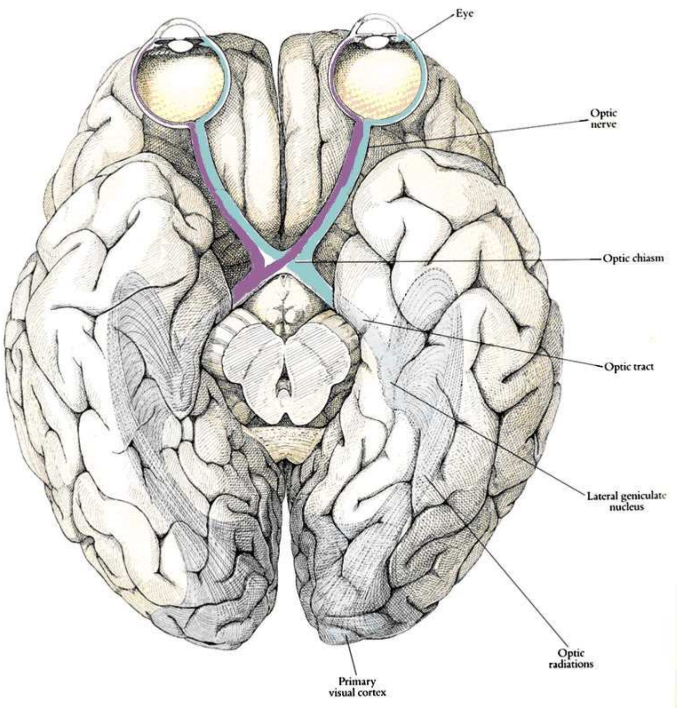


Figure 2.3: The human visual pathway: From the retinas to the primary visual cortex.

2.1.3 Color vision and color perception

Color is a subjective experience that is related to the spectral properties of light reaching our eyes. Color perception is the end result of some complex series of operations, it involves physical and psychophysical phenomena and is not yet fully understood. This section outlines some elementary facts about color vision. There are many benefits to the color vision ability; one advantage is surely the ability to distinguish and identify objects, and the ability to discriminate objects from the surroundings. Evolution has preserved color vision in humans, which leads to the thought that color provides an advantage over monochromatic vision. Basically, most of the color we see is determined by the light reflected from the surface of objects. Before discussing some of the principles of color perception it will be helpful to outline some of the fundamentals of the physics of light stimuli.

Light is defined as what is visible to the human eye. The visible spectrum is a small part of the electromagnetic spectrum, from a wavelength of 400 nanometers (short-wavelength light) to 700 nanometers (long -wavelength light).

A mixture of lights of different wavelengths can be seen as a rich range of colors. Thus, the ranges of colors we perceive in normal vision are the result of a mixture of light of different wavelengths. But the color of an object does not depend merely on the properties of the light reflected from it. For example, an object's appearance might change due to changes in the background against which it is seen. A more drastic example would be a "color blind" person, one who has a deficiency in color vision, that obviously does not view colors like a person with "normal" vision. Color vision is achieved by the cone photoreceptors located in the retina at the back of the eye.

Our retina is composed from a mosaic of four types of photoreceptors: Rods and the three types of cones. Each of these receptors contains a different pigment that differs in the range of light wavelength to which they are sensitive. The three cones' system is responsible for *photopic vision* (high luminance levels, high resolution, color vision) and the rods are responsible for *scotopic vision* (low luminance levels, low resolution, monochromatic vision). In the same manner as normal human vision uses the three cones system (*trichromacy*), color models and systems are designed with three primary colors. Although similar in their basic concept, these color systems and models are as a rule far less sophisticated than the color mechanisms that exist in the visual cortex. Psychophysical observations have demonstrated that these mechanisms encode color in the cortex in a more complex way than in the retina and the LGN [42].

2.1.4 Binocular Vision and Depth Perception

Human beings, like all predators, are equipped with two eyes that have overlapping visual fields (*binocular vision*). Vision, in general, is aimed toward recognizing and localizing objects. The purpose of binocular vision is to enhance vision by means of *stereopsis* which is a unique sensory mechanism. *Stereopsis* is a depth perception mechanism that depends on the use of both eyes. The human visual system uses two disparate images (via the two eyes) that are combined by the brain into a single image that yields a unified percept of depth, and contributes to distance judgment.

Although the visual system acquires two images in order to achieve stereopsis, it still retains a single representation of the world as viewed through the two eyes (the singleness of vision). Fusion is the sensory process that merges the two images into one, thus supporting stereopsis. Convergence (i.e., the eyes turn inward) and accommodation (i.e., changing focal power of the eye's lens) are controlled mainly by the binocular vision mechanism and are coordinated with each other in order to achieve clear vision and acute stereopsis. Stereoscopic images are very effective in improving interactions in a virtual environment. 3D vision adds a sense of realism that enhances the users' physical interaction, thus improving their control over virtual objects. Three dimensional accessories that take advantage of these properties, like 3D monitors and goggles, are rapidly evolving and are in common use in many home and industry applications.

Researchers of stereopsis come from a range of fields, since stereopsis has had an important contribution to areas like physiology, neurology, engineering, image processing and even art. Leonardo de Vinci (1452-1519), found that the depth of a scene could be represented in a painting by the appropriate combination of light, shade and perspective. He was the first to describe binocular parallax, and he actually discovered the monocular visual cues for depth perception. Sir Charles

Wheatstone showed in 1838 that two different perspective images observed through a stereoscope so that each eye observed only one view, yielded a three-dimensional image. He found that visual disparities produced by binocular viewing are related to depth perception and that the disparity is related to the lateral separation between the retinal images. Stereo vision had intensively been studied ever since. More than one hundred years after Wheatstone, Bela Julesz, created a pair of random dot patterns that became known as *Random Dot Stereograms*. Julesz [40] demonstrated that stereoscopic depth can be perceived without recognizing any objects. It was a remarkable finding about the visual system, that proved its ability to extract depth from disparity without the need of shape information.

This section reviews some of the basic principles of binocular vision and depth perception. For a more comprehensive review of these topics readers are referred to [32].

The Cyclopean Eye. Even though we view the world from two eyes that are placed in two separate locations, we see the world as if it is viewed from a single eye located between our two eyes [66]. The third eye is known as the it Cyclopean Eye and its location is called the *egocenter*.

Space Perception. The location of objects in space and the subjective appreciation of their relative or absolute position through vision can be referred to as visual space perception. The brain reconstructs a single perceptual image from the outside world through two retinal images. All of our visually based actions are reactions to the object's position in space. Moreover, they are based on a subjective perception of the world. Therefore, the visual perception must replicate the outside three-dimensional world as faithfully as possible.

Depth and Distance Perception. Localizing an object means judging its location relative to a reference point. When we judge the location of an object with respect to the egocenter, the judgment is called egocentric localization or absolute localization. Stereopsis is one of the many contributors to the distance component of visual localization.

The perception of the three-dimensional space can be divided into two parts: Absolute depth perception, also known as distance perception, and relative depth perception, also known as depth perception. Absolute depth perception is the judgment of how far an object is from the observer or from other objects. It includes the ability to judge the location of an object in absolute units of measurement (e.g., meter). Relative depth perception is the perception of relative proximity of one object to another or relative depth between two or more objects in the space. Binocular vision activates several special cues to distance and depth perception, including stereopsis. However, there are several monocular cues (that do not depend on the use of both eyes) that allow relative distance and depth to be judged (interposition, shading, texture, relative size, linear perspective, etc.). The brain uses numerous distance and depth cues to optimize the space perception.

Binocular Disparity. Binocular disparity is one of the most important and accurate depth cues. Binocular disparity (also known as relative disparity or retinal disparity) is the angular difference between the left and the right images, caused by the fact that the eyes are laterally separated (interocular separation of about 6.3 cm) and the objects are seen from slightly different view points.

Fusion. Fusion describes the neural process that brings the left and right retinal images from both eyes to merge and form one single image. Fusion takes place when the images are similar and it occurs in order to allow a single binocular vision. When two dissimilar images fall on corresponding areas of the retina, confusion exists due to the conflict between the two patterns. Suppression, superimposition or binocular rivalry, also known as retinal rivalry, may then occur.

Rivalry and Suppression. Suppression is a condition in which an image that was formed on the retina is not perceived and is mentally ignored (or neglected) either partially or completely [58]. It is one of the means the brain uses to overcome double vision. In general, the more dissimilarity exists between the images from the two eyes, the harder it is to fuse them into one. Suppression then occurs in order to eliminate one image and prevent confusion. If both eyes have equal dominance, there is an alternating suppression of the two images. Superimposition results in one compound image, where one image is presented on top of the other image. Binocular rivalry describes alternating suppression of the two eyes resulting in alternating perception of the two images. Incompatible stimuli, such as orthogonal gratings, presented dichoptically to the two eyes, are not fused into a single image. Instead, the monocular stimuli take turns in dominating perception. This phenomenon is known as binocular rivalry. Binocular rivalry involves a changing percept without any change in the retinal image. It provides a powerful tool for studying the perceptual process. It has been shown that rivalry is a process distributed across a hierarchy of visual cortical areas [3].

2.2 Depth and Color

Whereas depth perception is a valuable quality for navigation, orientation and performance in 3D applications, Color perception allows for better segmentation and evaluation of perceived objects [7, 59]. It allows the viewer to distinguish between different objects in the scene and between the objects and their background. Batavia et al. [7] have described an obstacle detection methodology for robotics, which combines color and stereo. Siegal and Akiya [59] have also showed that depth and color are tightly coupled. This is also valid for computer vision applications such as tracking multiple 3D moving objects (e,g, cars, humans) [101, 74]. For instance, Darrell et al. [17] combined depth from stereo with skin color and face detection in order to track moving people. Drascic and Grodski [23] have showed that the addition of a third dimension in human remote controlled teleoperation applications improve the decision making capabilities of the operator, while adding color improves the operator's recognition and obstacle detection performance. An integration of two detection methodologies, one using color segmentation and the other depth from stereo, enhances the efficiency of both.

2.3 Utilizing Properties of the Visual System for an Efficient Image Presentation and Compression

The visual pathway combines visual information from the sensory system, our both eyes. Some pre-computations are done by the retina prior to transmitting it towards the visual cortex and some signal processing is further done by the brain. The brain is a sophisticated and complex tool that enables us to perceive the outside world. The Computational aspects of the problem of stereo vision have received increased attention for it can be used in automatic systems that combine stereo vision. Marr [16] was the pioneer of the computational approach to vision. He considered the interpretation of the retinal image by the brain as the most important part of perception.

Many factors affect the retinal image quality starting from the visual scene (light scattering) trough the eye, (imperfect optic, chromatic aberration, diffraction) platform (head and eye movements) ending with the image processing conducted by the eyes and the brain. The eye's retina consists of about 100 millions of photoreceptors that are sensitive to light and convert the image into electrical signals. Other layers are involved in the signal processing in order to enhance the Signal-to-Noise ratio (SNR) and to maximize the information transmission. All visual information is conveyed to the brain through about 1 million fibers in the optic nerve. What means that compression is done.

2.4 Compression

Image compression is a reduction in the amount of data used to represent an image in order to meet bit rate or storage requirements, without impairing the quality of the reconstructed image beyond the minimal requirement for the intended application. Figure 2.4 present a general scheme to compression.

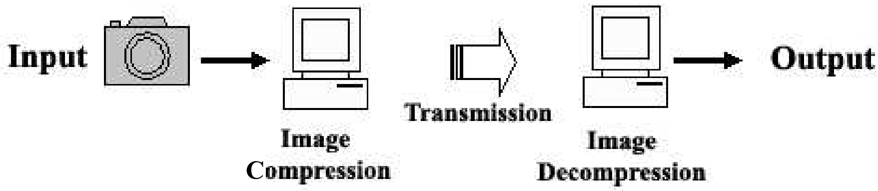


Figure 2.4: General compression scheme.

The amount of data that is needed to store, process or transmit a stream of single video imaging is relatively large. On top of these large storage requirements, the communication requirements are also immense. The number of bits required to represent a single color image is typically three times greater than the number of bits required to represent a single gray-scale image. Stereo color image, by nature, requires twice the amount of storage that a one color image requires, and six times the amount of storage of a single gray-scale image. Image compression plays an important role in the storage and transmission of color images. *Compression* is the process that reduces or eliminates redundant or irrelevant data from the signal. The term redundant data refers to the data that provide either no relevant information or information that is already known. Image compression addresses the problem of reducing redundant data in the image. The practical need for compression can be demonstrated in the following example: Given an RGB image with 1280 x 1024 pixels, 8 bits per pixel per each channel and frame rate of 30 frames per second, the required bit rate will be: 1280 x 1024 x 8 x 3 x 30 = 943,718,400 bits per second (bps). For a colored stereo image, the amount of transmitted data is doubled - resulting in a bit rate of 1,887,436,800 bps. The required bit rate for a gray-scale video stream will be one third of the above, i.e. 314,572,800 bps and two thirds for two gray-scale stereo channels. Obviously, reducing image resolution and the number of bits per pixel plays an important role in optimizing the bit rate. To transmit a color stereo pair in a network, for example at a maximum bit rate of 1.0 Mbps, we have to compress the video rate by at least 1887 times (1,887,436,800 bps, divided by the channel limitation of 1Mbps, and assuming channel utilization of 100

There are three basic data redundancies that can be identified in digital image processing: *Spatial redundancy, Temporal redundancy and Psychovisual redundancy*. Data compression is achieved when one or more of these redundancies are reduced or eliminated An extensive discussion on data redundancy can be found in [30].

Spatial redundancy. One of the common characteristics of a single image is that neighboring pixels are highly correlated. A pixel can be predicted from its neighbors, i.e, there is correspondence among pixels within an image frame. Data compression can be achieved by removing the redundancy within an image frame.

Temporal redundancy depends on the statistical correlation between pixels from successive frames. A large amount of temporal redundancy can easily lend itself to data compression (for example, Motion Compensated (MC) predictive coding).

Psychovisual redundancy originates from the Human Visual System (HVS) characteristics. It is well known that perception can be unaffected when less data is used to present important visual information.

To measure redundancy, we utilize the concept of Entropy from Information Theory, first introduced by Shannon [83, 82]. Information theory formulates a probabilistic view of information, and uses *Entropy* as a measure related to the average information content of a channel. Entropy is inversely proportional to redundancy.

Shannon's definition of entropy can determine the minimum channel capacity required to reliably transmit a source as encoded binary digits. While the channel capacity sets an upper bound on the bit rate, the entropy of a channel sets the lower bound on the bit rate [83, 82].

Chapter 3

Methods

This chapter summarizes the methods and techniques used in the controlled psychophysical perception experiments conducted with human subjects. All the protocols common to the various experiments are presented and discussed. Deviations for specific conditions are described in the appropriate chapter.

Several pairs of stereoscopic images were acquired by utilizing a stereoscopic photography system consisting of one digital color camera mounted on a horizontal stage which enabled offset adjustments. These pairs of stereo images were presented to subjects through two viewing apparatuses: A Stereoscope and a Head Mounted Display (HMD).

Section 3.1 describes the process of acquiring a stereoscopic image. Section 3.2 discusses methods of synthesizing and presenting a stereoscopic image to a human viewer. Moreover, it describes the two devices that were used in the current study. Section 3.3 discusses the image sets that were used in the different experiments. The experimental protocols and subject clinical requirements are discussed in Section 3.4.

3.1 Stereo Image Acquisition

The human visual system uses two disparate images, obtained via the two eyes, and combines them into a single image which yields stereoscopic depth perception. If the two pictures presented to the two eyes are taken from two different viewing points, stereoscopic imaging can be emulated. To accomplish this, a system comprised of two cameras can be used (or one camera with a horizontal offset ability). Each of the cameras acquires an image that will be presented to only one of the eyes. In order to present these images to a human subject, the viewing system has to interact with the stereoscopic ability of the human observer, taking into account his or her individual physical ocular parameters. These parameters vary significantly between subjects. The optical element of the eye can be modelled by a thin lens with a focal length ranging from 14 to 17 mm that adjusts to the focus for different viewing distances. For receiving a good stereoscopic image we need to consider the distance between the two eyes, referred to as the stereo base (IPD) (d in Figure 3.1), and find the optimal distance between the camera and the objects. The common range of the stereo base for an adult human is 63–70 mm. The optimal distance suited for a stereo base of 70 mm is 1 to 1.4 m (Z in Figure 3.1). Shorter distances can cause hyperstereo (and headache) while longer distances might cause loss of stereopsis. Figure 3.1 displays the optical configuration of a two-camera stereoscopic photography system, placed in the X-Y plane. The system consists of one color and one monochromatic camera designed as a MIX configuration. It is the basis of this dissertation (Figure 3.1).

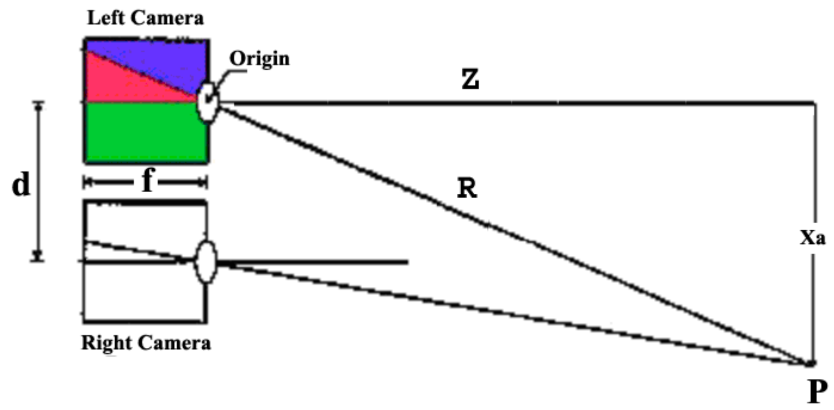


Figure 3.1: A two camera stereoscopic image acquisition system

The distance d between the two cameras described in Figure 3.1 can be adjusted, so that an observer viewing with the right eye an image obtained by the right camera, and with the left eye an image obtained by the left camera, will be able to fuse them into one stereoscopic image. The two cameras have the same focal length and are set at a distance d (stereo base) from each other. Both cameras are placed in the X–Y plane at a distance Z from the objects. When creating a stereoscopic still image of non-moving objects, the same camera can be used to obtain both the right and the left eye images by shifting it by distance d after taking the first photograph. Focusing on a specific point enables the observer to comfortably view a 3D image for all points close to the focusing point. By focusing at infinity and maintaining the optical axes parallel, the entire scene can be fused into a 3D image.

To create the still images used in the experiments, one high resolution digital color camera (NIKON D2X, Fuji S2) positioned 1.3 m from the objects was used with a horizontal offset ability (Figure 3.2). The stereo base was 10 cm. Indirect lighting conditions were used in order to maintain uniform illumination.

3.2 Stereo Image Presentation

In order to fuse a stereo pair presented to a subject into one image, each eye must see its appropriate image. An external device can be used for viewing the stereoscopic images. Various external apparatus exist, such as shuttered goggles, anaglyph, polarized goggles etc. The devices that were used in this research are a stereoscope and an HMD. The advantage of using a stereoscope is its relative simplicity (no

Figure 3.2: The camera mounted on the horizontal stage; (in the smaller picture - the lateral movement mechanism)

calibration is needed). The HMD, on the other hand, being computer controlled, enables a procedure of automatic display of images with multiple repetitions.

The First apparatus used was a 1905 stereoscope (Figure 3.3). The stereoscope is designed to display two photographs to the viewer's eyes, using a partition that enables each eye to view only one of the two pictures. The two pictures are positioned on a stiff mounting, side by side, and viewed through a set of prisms and lenses. The distance between the lenses and the images is adjustable. Since the invention of the stereoscope by Wheatstone in 1838, the stereoscope has been utilized in many experiments involving binocular vision. The stereoscope has provided a convenient tool to study many other binocular phenomena such as fusion, color mixing, suppression and rivalry. It supports dichoptic stimulation (different monocular stimuli imaged separately to the left and right eyes) in stereoscopic vision. For example, in studies of binocular rivalry, one image is presented to one eye and a very different image is presented to the other eye yielding a competition between the two eyes. In studies of color mixing, a red circle is presented to one eye, while fuse with a green circle presented to the other eye. In our study, a gray-scale image is presented to one eye and a color image is presented dichoptically to the other eye .

Before each experimental session the subjects were asked to adjust the distance between the color stereo pair (stereogram) and the lenses until that a single 3D image was comfortably binocularly observed.

Figure 3.3: A 1905 stereoscope

The second apparatus used is a Head Mounted Display (HMD) (Figure 3.4). Experimenting with an HMD allows recent technological developments to achieve 3D realism based on new display techniques. These technologies might introduce elements such as refresh rates that might cause the visual system to perform differently than under conditions of a stereoscope. Using the HMD, each eye has its own CRT display. The HMD experiment, whose intent was to establish the phenomenon under more application-like conditions, makes use of an nVisor-SX display controlled by a PC computer. The nVisor-SX is usually used for advanced virtual reality applications. It incorporates high resolution color micro-displays with custom engineered optics designed to deliver high visual acuity in a wide field-of-view format. The nVisor-SX specifications are: Dual channel support (stereo), Monocular FOV (diagonal) 60 degrees, an overlap of 100%. It has access to user adjustments including inter-ocular distance, and an eye-relief to accommodate users with eyeglasses.

Before each experimental session the subjects were asked to make adjustments until a single 3D image was comfortably binocularly observed. The HMD experimental setup Figure 3.5 enabled a computer controlled procedure of an automatic display of images with multiple repetitions.

3.3 The Image Sets Used in the Experiments

This Section presents the various images used in the experiments. The images used with the stereoscope are presented in Section 3.3.2. The images used with the HMD are presented in Section 3.3.3.

3.3.1 Chromatic combinations of the stereo pairs

Each image set comprised a four chromatic combinations of the same basic pair of stereo image. The basic stereo pairs acquired were colored images. In order to create a MIX pair, both the left and the right image were converted to a monochromatic

Figure 3.4: The nVisor-SX HMD (Head Mounted Display)

(gray-scale/Black and White) image. The gray-level conversion was obtained by transforming the color image into L*a*b color coordinates, and then extracting only the luminance (L) component.

The L*a*b color model is based on the model proposed by the Commission Internationale d'Eclairage (CIE) in 1931 as an international standard for color measurement. In 1976, this model was named CIE L*a*b. L*a*b color space is designed to be device independent, creating consistent color regardless of the device. In addition, this color space is more perceptually linear than other color spaces (for example RGB). L*a*b color consists of a luminance or lightness component (L) and two chromatic components: The a* component (from green to red) and the b* component (from blue to yellow). The left and right images of each image set are combined into the following four configurations:

- Left eye: Color image. Right eye: Color image (Col-Col).
- Left eye: Gray-scale image. Right eye: Gray-scale image (BW-BW).
- Left eye: Color image. Right eye: Gray-scale image (MIX).
- Left eye: Gray-scale image. Right eye: Color image (MIX).

3.3.2 Image sets used with the stereoscope

In the experiment that was conducted with the stereoscope two sets of stereo image pairs were used. One set of stereo images was dominated by low saturated yellow colors, and included three objects positioned at various distances from the camera, against a neutral homogenous background (These images will be referred to as the *Yellow image set*)(Figure 3.6). This set of images was taken using the camera set as described in Section 3.1.

The second set of images included color-saturated objects presented against a cluttered background of colorful content, were mainly green and magenta in color (This set of images will be referred to as the *Magenta image set*) (Figure 3.7). The Magenta set was modified from [76, 77].

Figure 3.5: The HMD experimental setup

3.3.3 Image sets used with the HMD

Three sets of stereo image pairs were used in the experiments with the HMD . Each set contained different objects at different distances and different colors. The first set of stereo images (Figure 3.8) included four colored objects (red, green, yellow and blue) at different distances positioned in front of a homogeneous monochromatic background (uncluttered). In the second set of stereo images (Figure 3.9), the same objects were used, with more objects added in the back, but keeping the background homogenous and monochromatic. The third set of the images (Figure 3.10), contained two greenish objects at two different distances from the camera. Overall, the three image sets covered a range of chromatic contents, in terms of hues and saturation. The variety was intended to sample a range of colors, distances, inter-positions, and saturations [1].

3.4 Experimental Procedure

3.4.1 Subjects

Seven different experiments were carried out. A total of 42 subjects participated. The number of subjects that participated in each of the experiments is reported

[1] All images were taken by the Photographer Yoav Elkoby: http://www.eyph.com/

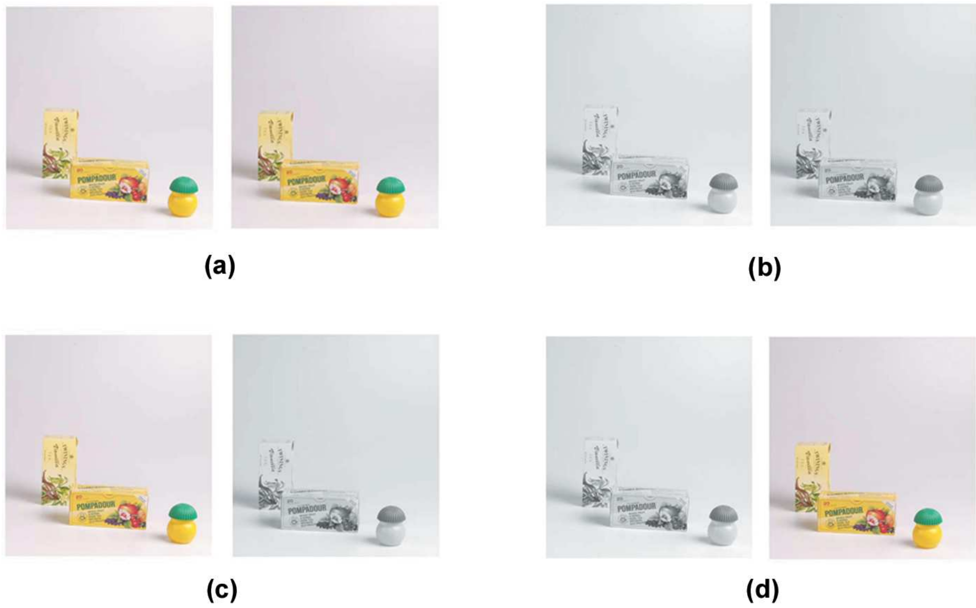


Figure 3.6: Four stereo combinations used with the stereoscope - *Yellow image set*. (a) (Col-Col); (b) (BW-BW); (c) MIX (Col-BW); (d) MIX (BW-Col)

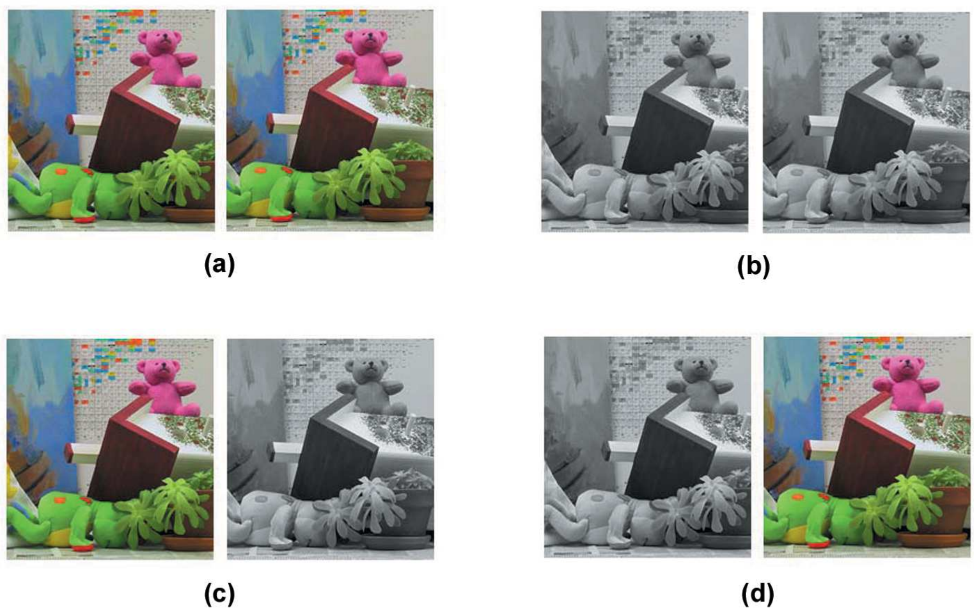


Figure 3.7: Four stereo combinations used with the stereoscope. *Magenta image set*. (a) (Col-Col); (b) (BW-BW); (c) MIX (Col-BW); (d) MIX (BW-Col)

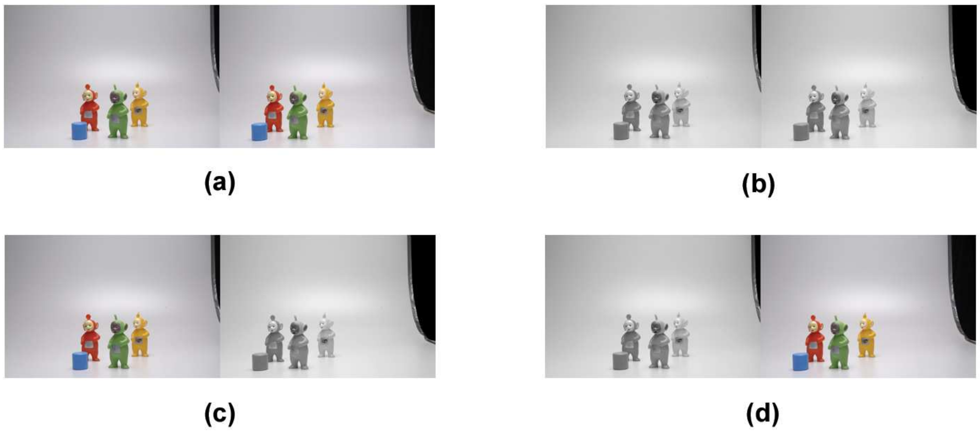


Figure 3.8: First HMD set: Four stereo combinations of the *T3 image set* used in the HMD experiment. (a) (Col-Col); (b) (BW-BW); (c) MIX (Col-BW); (d) MIX (BW-Col)

separately, in the chapters discussing the results of each experiment. All subjects were clinically tested to ensure they had normal color and depth perception and equal visual acuity in both eyes, as determined by optometric examinations using standard non-invasive vision tests as described below. All subjects had normal or corrected to normal vision. All subjects had equal Snellen acuity in the two eyes of at least 6/7.5. Differences of one half line acuity between the eyes eliminated a candidate from the study. Constant, intermittent strabismics and subjects with a history of strabismus surgery were not included in the study. All Subjects had normal stereo acuity. Stereo-acuity was tested via the Titmus Stereo Fly test and was 40" in all subjects. Color vision was normal and tested using Ishihara plates.

3.4.2 Protocol

For each subject several presentations of each one of the four combinations of the stereo pairs were performed. The protocol follows:

1. The images were presented dichoptically (stereoscope or HMD) at an adjustable distance from the eyes.

2. The stereoscope cards were illuminated from above.

3. Subjects were asked to adjust the focal distance for both apparatus (and the interocular distance in the HMD) for their comfort.

4. In order to allow proper grading of the color and depth obtained from the perceived images, the subject first observed (through the apparatus) a full color stereo image (Col-Col stereo pair) as a reference to a full color 3D image followed by the full gray-scale stereo image (BW-BW stereo pair) as a reference to a full gray scale 3D image.

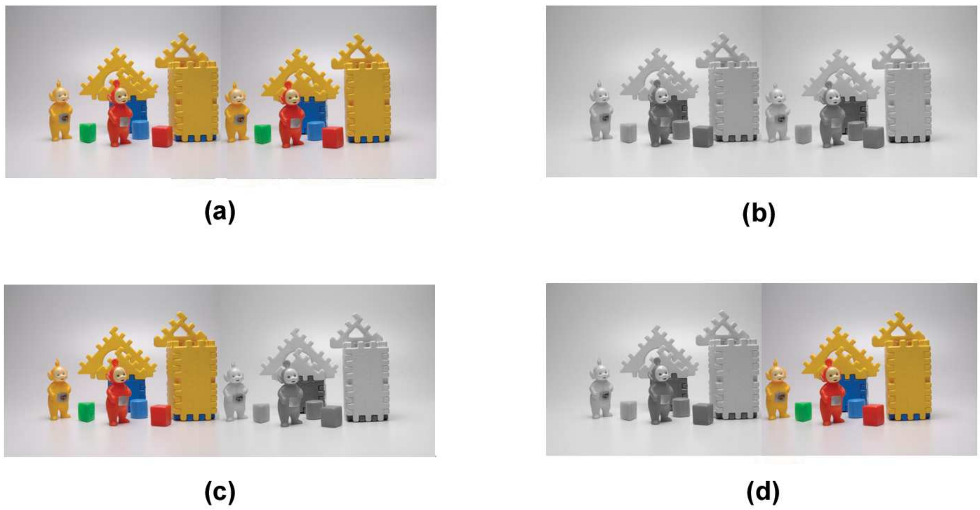


Figure 3.9: Second HMD set: Four stereo combinations of the *TH image set* used in the HMD experiment. (a) (Col-Col); (b) (BW-BW); (c) MIX (Col-BW); (d) MIX (BW-Col)

5. The images were presented randomly.
6. The subjects were neither aware of the color content of the images nor the purpose of the experiments.
7. The subjects were asked to look at the stereo pair with both eyes opened.
8. Unlimited time of exposure was available
9. Subjects were asked to rate their color perception on a scale of 1 to 10, with 1 denoting a gray-scale image and 10 an image in vivid colors. They were also asked to rate the depth perception from 1 to 10, with 1 corresponding to a flat image with no depth at all and 10 to a full 3D image.

Figure 3.10: Third HMD set: Four stereo combinations of the *Bu image set* used in the HMD experiment. (a) (Col-Col); (b) (BW-BW); (c) MIX (Col-BW); (d) MIX (BW-Col)

Chapter 4

The Basic Effects: Depth and Color Perception Under MIX Conditions

The questions to be resolved in this Chapter are whether the stereo image will give an impression of depth despite the difference in chromatic content and whether rivalry occurs between the color and the gray images. If rivalry, which is is a bi-stable perception phenomenon associated with viewing two competing stimuli, occurs, will it take the form of: 1) suppression at random appearance (alternation between color and gray-scale), 2) suppression of one eye (eye dependent), or 3) suppression of the gray-scale image or suppression of the color image (chromatic dependent). Various combinations of color and gray-scale images were presented to the subjects using either a stereoscope or an HMD (Section 3.2).

Experiments were conducted to confirm the the proposed technique. Section 4.1 discusses the motivation for using a MIX stereo pair. Section 4.2 discusses related work regarding color and depth studies in accordance with the current research. Section 4.3.1 describes experiments carried out with a stereoscope to examine depth and color perception under MIX conditions. Section 4.3.3 discusses similar experiments carried out using an HMD. All results are discussed within the context of the experiments [93].

4.1 Motivation

Color and depth perception are important capabilities in every-day human activities and in many applications that require human supervision or control. These two aspects are tightly coupled in computer vision and teleoperation applications (Section 2.2.

Vision systems favor taking advantage of both properties in their defined requirements. While depth perception, through binocular vision, provides us with the ability to determine the 3D structure and the distance of objects, color perception allows for segmentation and evaluation of the perceived stereoscopic image. *Stereopsis*, which is perhaps the most important mechanism of depth perception, depends on the use of both eyes but it does not depend on the color content of images [91]. An overview on binocular vision, stereopsis and depth perception can be found in Section 2.1.3. Relevant background concerning color vision is presented in Section

2.2.

Unfortunately, color stereoscopic imaging requires large transmission capacity. Since channel bandwidth is a costly commodity, there is a motivation to reduce it to a minimum. Some approaches to this challenge focus on optimal compression and optimization of both images by various means [79, 80, 81, 97]. Another approaches exploit the fact that the left and right images differ only in small areas, and achieve improved compression by taking advantage of the redundancies in the stereo pair. These techniques often rely on disparity compensation [98, 100]. Other investigators have suggested relying on the versatile capabilities of the human visual system to further reduce the bandwidth requirements of the stereoscopic color image. Section 2.4 includes a review of related work concerning compression.

The results of the current research would enable to reduce the amount of information coming from a 3D color scene by reducing one of the images to a gray-scale image (MIX configuration), thus reducing the amount of data transmitted by a third even before any other means of compression is applied. Other compression methods can then be applied to further improve bandwidth efficiency. Moreover, as opposed to nearly all of the techniques used for stereo compression, which assume at least two similar cameras in terms of chromatic information, this approach requires only one of the cameras to be a color camera.

4.2 Related Work

Several previous studies deal with the mutual impact of binocular vision and color. The role of color in binocular vision is still controversial. It has been argued that color information contributes to binocular depth perception although, color is not necessary for achieving binocular vision. For instance, it is well known [89, 18, 38, 39] that chromatic information helps address the correspondence problem in stereo vision. According to Shevell et al. [84], only a small difference in chromatic adaptation is caused by introducing a three-dimensional representation of the stimuli. This implies that color and depth perception are only loosely coupled and therefore might be processed separately. There is evidence of a reduced contrast threshold for binocular detection as compared with monocular detection [88]. This means that there is a sort of inter-ocular facilitation that enhances binocular performance in detection tasks [5]. An independent chromatic and achromatic stereopsis mechanisms were proposed by Kingdom and Simmons [87, 47, 46, 89]. Thus, investigators have examined approaches in which two different images are presented to the two eyes. Such a procedure may result either in a fused stereoscopic image or in *binocular rivalry*, Which is a form of multi-stable perception that occurs when the two eyes are presented with visual stimuli that are different from each other and cannot be fused into a single coherent percept. Under these conditions, the perception typically alternates between two states corresponding to the left or right eye's stimulus. Reviews and a summary of work on binocular rivalry can be found in [28, 32, 70, 11, 3, 69].

The current research for the current research calls for presenting two images that differ in their *chromatic* content to the two eyes. There was uncertainty whether the color and gray-scale images undergo fusion or rivalry. Previous work has examined fusion or rivalry between competing colors, not between color and lack of color. Gunter [73] used red and green stimuli, and found that color fusion was achieved even when the two stimuli were presented alternately to both eyes. This implies that the color fusion was the result of a central process. Perry et al. [65] confirmed this finding by showing that red and green stimuli can be fused into yellow when presented dichoptically (under intermittent vision). Andrews et al. [4] have reported that when two different colored panels are presented to a subject, the perception often alternates between the two colors. Julesz [41] reported that two images of different colors can create the impression of a third, mixed color [26]. This percept is known as binocular color mixture. Makous and Pulos [61], reported that during binocular rivalry between a red and black grating, and a perpendicular green and black grating, the colors mixed, and the observer reported seeing alternation between perpendicular yellow and black gratings. In other words, there is some form of integration of the colors seen by the two eyes. Treisman [94] showed that depth perception was not affected by the existence of rivalry or suppression between incompatible colors, even when rivalry causes the suppression of color information. Also, information of contour and positions remained intact during such color suppression. Given the query of whether fusion or rivalry will occur in the case of MIX image, we were further encouraged by Andrews and Lotto [4] who have shown that when physically different monocular stimuli are likely to represent the same object at the same location in space, fusion is likely to occur. Moreover, there is evidence that even in the case of rivalry, information from the suppressed eye is still processed in the brain, i.e., the eye's sensitivity is reduced but not shut off. Abruptly increasing the luminance of or moving an object seen by the suppressed eye will cause it to be detected [29, 96].

4.3 Experimental Procedure

4.3.1 Using a stereoscope

A stereoscope was used in these experiments to observe the images (Figure 3.3). These experiments were performed on 11 subjects (9 males and 2 females) between the ages of 16 and 45. All subjects were clinically tested for normal color and depth perception and equal visual acuity in both eyes (Section 3.4.1). Except for two subjects, all subjects were naive as to the purpose of the experiments. Two sets of stereo image pairs were used: The *Yellow image set* (Figure 3.6) and the *Magenta image set* (Figure 3.7). For details see Section 3.3.2. In each set, four different combinations of image pairs were used:

1. Left eye: Color image, Right eye: Color image (Col-Col).
2. Left eye: Gray-scale image, Right eye: Gray-scale (BW-BW).
3. Left eye: Color image, Right eye: Gray-scale image (MIX).
4. Left eye: Gray-scale image, Right eye: Color image (MIX).

The image pairs were presented in random order; each set was presented twice. For each image pair, subjects were asked to rate their color perception on a scale of 1 to 10 (Section 3.4.2).

4.3.2 The stereoscope results

Depth Perception Under MIX Conditions

Depth was perceived in all four combinations of stereo images and in both image sets that were presented to the subjects. Color rivalry, if it occurred, seemed to have no influence on depth perception. The results across the 11 subjects are summarized in Table 4.1, and graphically presented in Figure 4.1. Figure 4.1-a shows the results averaged over all subjects. Figure 4.1-b shows the average for each subject individually.

In table 4.1 the row marked "Mean" includes the mean results (across 11 subjects, multiple viewings per subject, both sets of images). The row marked "Std." includes the Standard Deviation for these mean values. Columns refer to the content of the presented stereo pairs. The column labeled "MIX Pair" includes both the Col-BW and BW-Col presentations.

	Color Pair	**MIX Pair**	**Gray-scale Pair**
Mean	9.62	9.35	9.20
Std.	0.92	1.38	0.96

Table 4.1: Depth perception scores (stereoscope, scale [1-10])

Figure 4.1-a shows the same results graphically: The leftmost bar indicates the mean depth perception result for the Col-Col images; the middle bar shows the mean results for the MIX images; and the rightmost bar indicates the results for the BW-BW images. The offset indicators on each bar show the extent of the Standard Deviation.

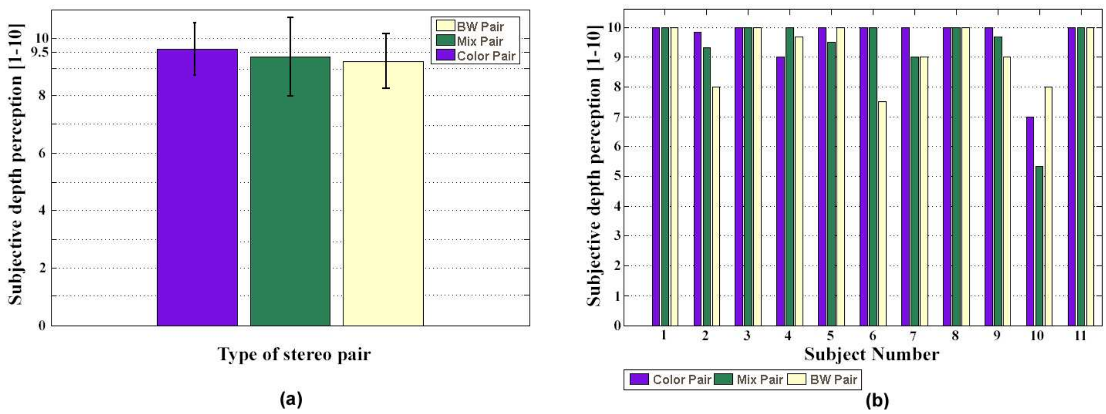


Figure 4.1: (a) Depth perception of three types of stereo pairs (stereoscope) (b) Subjective depth perception (stereoscope)

Figure 4.1-b shows the individual average results for each subject. Each of the 11 triplets of bars corresponds to one subject. The order of the bars within each triplet is the same as in Figure 4.1. The Y-axis denotes the score on the scale of

1–10 described earlier. The X-axis separates the different subjects. Here, for each subject, the result is their average across both image sets (Figures 3.6 and 3.7).

In summary, depth perception seems to be unaffected by the use of MIX pairs. Average depth scores for all 3 presentations (Col-Col, MIX and BW-BW) show insignificant differences (maximum difference obtained for color pair-monochromatic pair has a paired, two-tailed *t-test* value of $p = 0.21$).

Color Perception Under MIX Conditions

All subjects reported that they perceived a color image when they were presented with one color image and one gray-scale image (MIX pair), as well as when viewing two color images. The mean and Standard Deviation results are shown in Table 4.2. The average color score is 9.56 (Std. 0.92) in the Col-Col pairs, and 7.37 (Std. 1.55) in the MIX pairs. Indeed, some subjects reported a color fading effect when viewing some images. Also, some subjects reported that the color of some of the objects within an image faded in and out during viewing. These reports were not consistent for the same subject across different viewings, or for the same image pair across subjects.

Results are presented in Table 4.2 and plotted in Figure 4.2-a. The average results for each of the 11 subjects is shown in Figure 4.2-b. The axes are the same as in the respective depth perception figures (Figures 4.1-a,b).

	Color Pair	MIX Pair	Gray-scale Pair
Mean	9.56	7.37	1
Std.	0.92	1.55	0

Table 4.2: Color perception scores (stereoscope, scale [1-10])

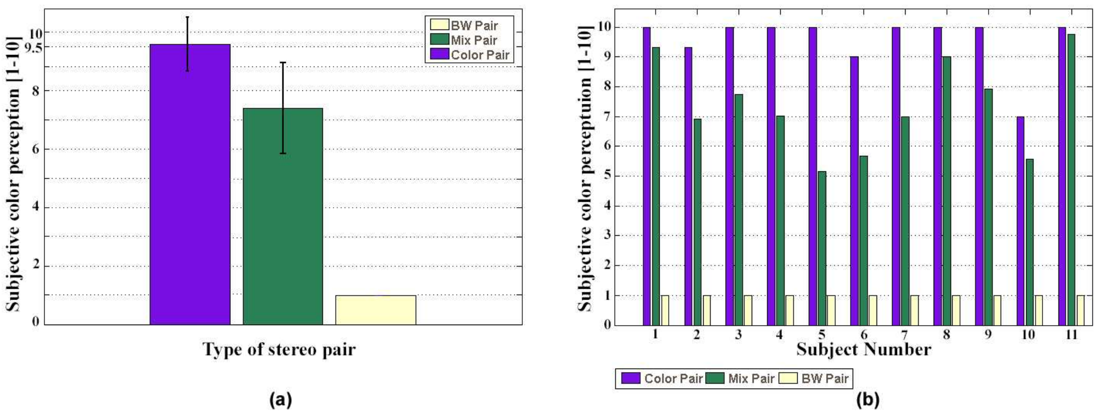


Figure 4.2: (a) Color perception of three types of stereo pairs (stereoscope) (b) Subjective color perception (stereoscope)

The results show that subjects clearly perceived color in the MIX presentations. There was, however, a certain amount of degradation in the quality of the perceived color. In order to ascertain whether the degraded color perception in the MIX condition more closely resembled the color pair or the monochrome pair, average color perception differences were calculated in pairs, (i.e., for each subject separately), and for the group. These are presented in Table 4.3. The Table shows that the difference in results between the Col-Col images and the MIX images is smaller than the difference between the MIX images and the gray-scale (BW-BW) images. This difference is statistically significant (paired one-tailed *t-test*, $p = 0.0005$). However, given that the measures are on an ordinal scale, rather than interval, we cannot completely reject the null hypothesis that the results from the MIX presentations are not closer to the color presentations, than to the monochrome presentation.

	Color - MIX	**MIX - BW**
Mean	2.2	6.37
Std.	1.33	1.55

Table 4.3: Color difference distance results (stereoscope)

The above results were obtained after averaging both image sets. In addition, the same analysis was performed separately on each of the two image sets, in order to test whether these effects depend on the specific characteristics of the image content or whether they can be generalized. In order to ascertain whether the degraded color perception in the MIX images for each of the image sets more closely resembles the color pair (Col-Col) or the monochrome pair (BW-BW), average color perception differences were calculated in pairs, (i.e., for each subject separately), and for the group as a whole. These color differences are presented in Table 4.4.

Results show that the difference in color perception scores between the Col-Col images and the MIX images is smaller than the difference between the MIX images and the gray-scale (BW-BW) images. This difference is statistically significant for both *Magenta image set* and *Yellow image set* (paired one-tailed t(19)=5.38, $p = 3.4e - 5$, and paired one-tailed t(19)=14.23, $p = 1.38e - 11$, respectively).

Table 4.4 summarizes the mean and Standard Deviation (Std.) of the color score differences between the MIX pair and the gray-scale pair (MIX minus BW) and the color score differences between the full color pair and MIX pair (Color minus MIX). The color score differences were calculated for each of the two stereo sets separately. Figure 4.3 graphically presents the same results that are presented in table 4.4. The two left bars refer to the *Magenta image set* and the two right bars refer to the *Yellow image set*. Within each group, the left bar represents the difference in color perception between the Col-Col pair and the MIX pair (Color minus MIX) and the right bar represents the difference in color perception between the MIX pair and the gray-scale pair (MIX minus BW). As can be clearly seen from the graphs, the *Yellow image set* MIX pair is closer to a full color perception than the *Magenta image set* MIX pair.

Although significance was evident for both image sets *Magenta image set* and *Yellow image set*. The score difference was larger for the *Yellow set*, indicating even a smaller degradation of color perception due to the introduction of a MIX pair.

Magenta Image Set		
	Color - MIX	**MIX - BW**
Mean	2.97	5.85
Std.	1.27	1.19
Yellow Image Set		
	Color - MIX	**MIX - BW**
Mean	1.46	7.41
Std.	0.95	0.96

Table 4.4: Color perception difference by image set (stereoscope). Means and Standard Deviation (Std.) of color perception Difference for both *Magenta* and *Yellow* image sets

4.3.3 Using an HMD

In the second experiment the stereoscope was replaced by an HMD. These sets of experiments tested the hypothesis with an HMD controlled by a PC (see Section 3.2 for details). These experiments were performed on 15 subjects (10 males and 5 females) between the ages of 21 and 43. All subjects were clinically tested as discussed in Section 3.4.1.

Three sets of stereo image pairs were used. The first set of stereo images (Figure 3.8) will be refereed to as *T3 image set*. The second set of stereo images (Figure 3.9) will be refereed to as *TH image set* and the third set of the images (Figure 3.10) will be refereed to as *Bu image set*. In each set, four different combinations of image pairs were used (Col-Col, Col-BW, BW-Col, BW-BW) (see Section 3.3.3 for details).

A total number of 12 stimuli were presented in random order; each stimuli was presented ten times. Subjects were asked to rate their depth and color perception on a scale of 1 to 10 (Section 3.4.2).

4.3.4 The HMD results

Depth Perception Under MIX Conditions

Depth was perceived in all 4 combinations of stereo images and in all 3 image sets that were presented to the subjects. The results here were even more impressive than in the stereoscope experiments as can be seen in Table 4.5, and graphically in Figure 4.4. All subjects in all viewings rated depth as a maximum (10). Figure 4.4-a shows the average results for all subjects. Figure 4.4-b, shows the average for each individual subject. Table 4.5 is arranged the same as Table 4.1, and Figure 4.4 parallels Figure 4.1. In summary, when using an HMD, depth perception is unaffected by the use of MIX pairs of images.

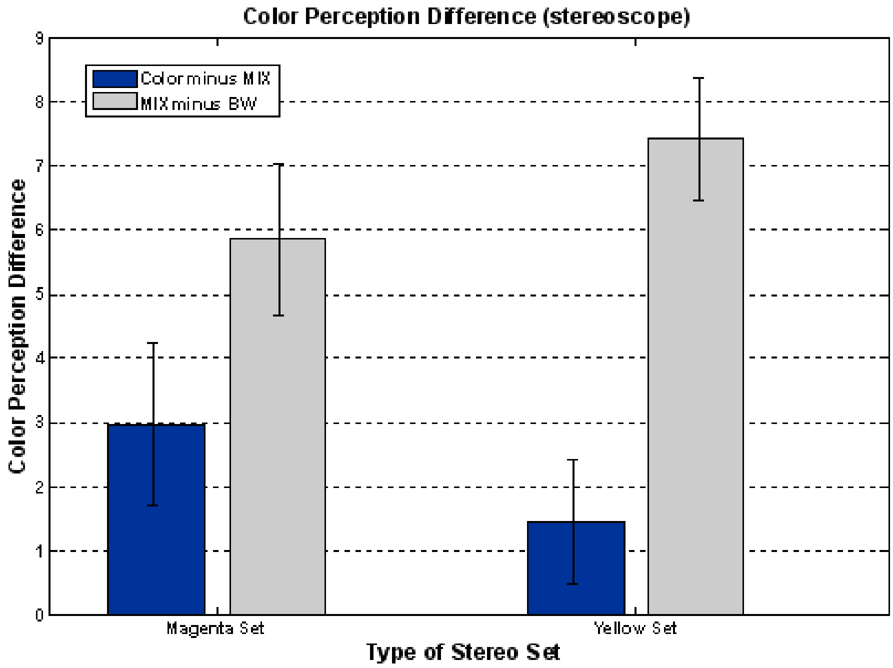


Figure 4.3: Color perception difference for both image sets . The color difference results presented are: (Color minus MIX) and (MIX minus BW). (a) Left group - The *Magenta image set*; (b) Right group - The *Yellow image set*

	Color Pair	MIX Pair	Gray-scale Pair
Mean	10.00	10.00	10.00
Std.	0.0	0.0	0.0

Table 4.5: Depth perception scores (HMD, scale [1-10]

Color Perception Under MIX Conditions

In these experiments the overall stimuli per subject were greater than in the stereoscope experiment (overall 30 stimuli per subject were presented for each one of the four stereo combinations).

With the HMD, all subjects reported that they perceived a color image when they were presented with one color image and one gray-scale image, as well as when viewing two color images. The mean and Standard Deviation results are shown in Table 4.6. The average color score is 9.95 (Std. 0.18) in the Col-Col pairs, and 7.20 (Std. 0.92) in the MIX pairs. Here too, some subjects reported a color fading effect when viewing some MIX pairs or reported that the color of some of the objects within an image faded in and out during viewing. These reports were not consistent for the same subject across different viewings, or for the same image pair across subjects. The averages of the color perception results for all subjects are presented in Table 4.6 and Figure 4.5-a. The average results for each of the 15 subjects is shown in Figure 4.5-b. The axes are the same as in the respective depth perception figures, (Figures 4.2-a,b).

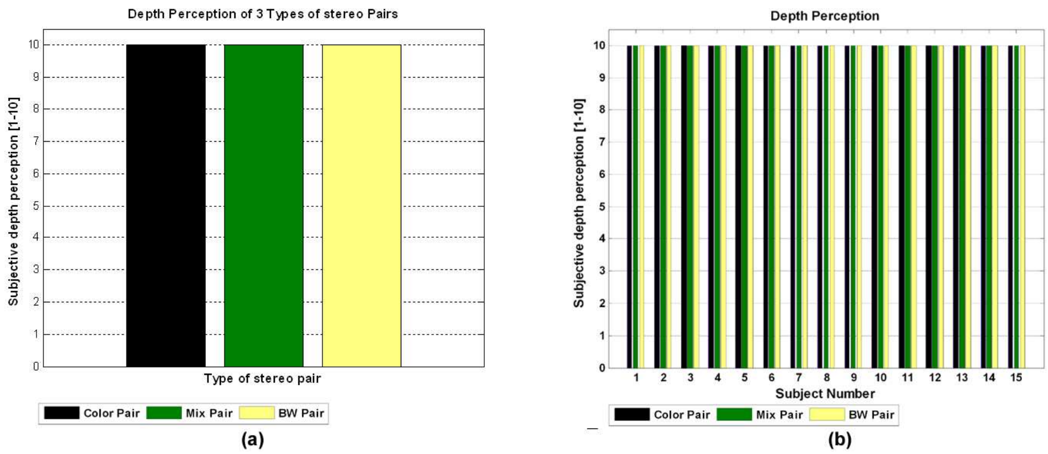


Figure 4.4: (a) Depth perception of three types of stereo pairs (HMD) (b) Subjective depth perception (HMD)

As with the stereoscope, the results clearly show that in a MIX presentation the subjects perceived a 3D color image, but with color that was of a slightly degraded quality. Here too, average color perception differences were calculated in pairs (i.e., for each subject separately), and for the group as a whole. The group results are presented in Table 4.7. The Table shows that the difference in results between the Col-Col images and the MIX images is smaller than the difference between the MIX images and the gray-scale (BW-BW) images. This difference is statistically highly significant (paired one-tailed *t-test*, $p = 1e-17$).

	Color Pair	**MIX Pair**	**Gray-scale Pair**
Mean	9.95	7.20	1.01
Std.	0.18	0.92	0.05

Table 4.6: Color perception results (HMD)

	Color - MIX	**MIX - BW**
Mean	2.7	6.18
Std.	0.83	0.9

Table 4.7: Color difference distance results (HMD)

The above results were obtained after averaging both image sets. In addition, the same analysis was performed separately on each of the two image sets, in order to test whether these effects depended on the specific characteristics of the image content or whether they can be generalized. In order to ascertain whether the degraded color perception in the MIX images for each of the image sets more closely resembles the color pair (Col-Col) or the monochrome pair (BW-BW), average color perception differences were calculated in pairs, (i.e., for each subject separately),

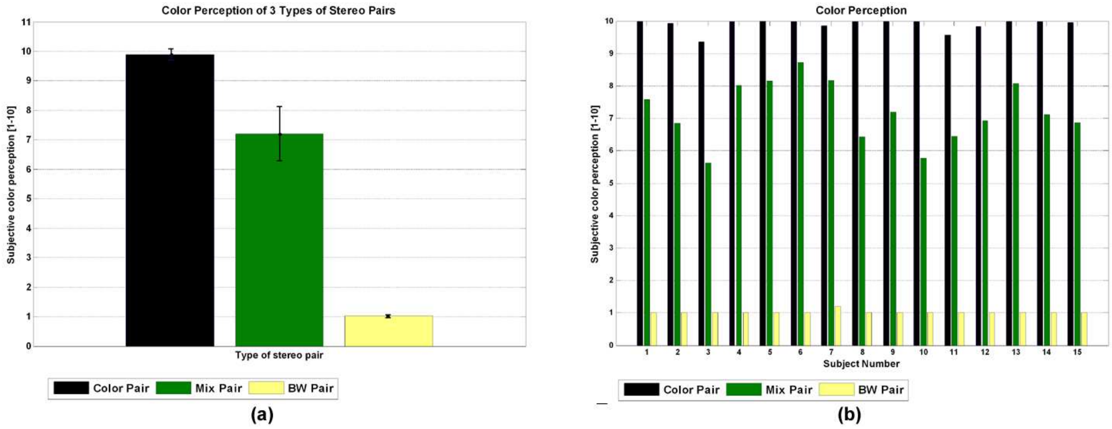


Figure 4.5: (a) Color perception of three types of stereo pairs (HMD) (b) Subjective color perception (HMD)

and for the group as a whole. These color differences are presented in Table 4.8 and in Figure 4.6. Results show that the difference in color perception scores between the Col-Col images and the MIX images is smaller than the difference between the MIX images and the gray-scale (BW-BW) images. A *t-test* for paired samples was conducted separately for each of the three image sets between the two scoring differences (Col-Col minus MIX) and (MIX minus BW). The *t-test* revealed that this difference is statistically high for all three image sets *Bu image set*, *T3 image set* and *TH image set*. (paired one-tailed t(14)=3.10, $p = 0.008$, and paired one-tailed t(13)=6.64, $p = 1.6e-5$, paired one-tailed t(13)=8.79, $p = 7.91e-7$, respectively).

Table 4.8 summarizes the mean and Standard Deviation of the color differences between the full color and MIX images (Color minus MIX) the MIX pair and the gray-scale image (MIX minus BW) for all three image sets. Figure 4.6 graphically presents the color perception differences for all sets.

4.4 Conclusions

The experiments demonstrate that when two stimuli that differ in chromatic content were viewed dichoptically, the images from both eyes fused into a 3D image that always appeared in color.

The results show that as a rule, subjects successfully fused the MIX images in all sets. Subjects perceived a 3D image in terms of depth, irrespective of the color differences in a given image pair. Color perception was achieved in all MIX cases, even though some degradation of color quality can be seen in the results.

It is known that the sameness of color in a stereoscopic pair can act as a stereopsis cue [94] and that different stimuli presented dichoptically to each eye usually cause rivalry (see Chapter 8) . This rivalry implies that the visual system cannot perceive a stable perception of the stimuli obtained from the two eyes and it either rejects one of the images or alternates between them in unstable state. Since the visual system

Bu Image Set		
	Color - MIX	**MIX - BW**
Mean	3.6	5.29
Std.	1.03	1.06
T3 Image Set		
	Color - MIX	**MIX - BW**
Mean	2.09	6.78
Std.	1.27	1.38
TH Image Set		
	Color - MIX	**MIX - BW**
Mean	2.25	6.67
Std.	0.92	0.97

Table 4.8: Color perception difference by image Set (HMD). MIX minus BW - the color difference between the MIX pair and the BW pair. Color minus MIX - the color difference between the full color pair and the MIX pair.

can achieve balance by suppression in cases of dissimilar images that are presented to the two eyes, and since the system seeks strong perceptive coherence, we believe that the channel that carries the color information has more weight than the channel that carries the monochromatic information, which is likely to be partially or totally suppressed.

These results clearly show that the interaction of the MIX stimuli between the two eyes is possible and confirm that the color mechanism involved in this process must be beyond the monocular mechanism in the cortex. Moreover, since a 3D image is obtained regardless of color content, the color generation is binocularly driven and it takes place later in the cortex. The color reproduced in the interocular interaction is not limited to a specific color content of the image although better results were obtained with unsaturated color content (the *yellow image set*). Our results are consistent with the findings of Land [50, 64], that the color generating mechanisms are combined of two stages, located at different sites of the human brain: The first stage does not include any binocular neurons and merely compares color (wavelength) information across space, whereas the second is binocular in nature, since it occurs after the convergence of the input from the two eyes and combines the results of the first stage. Land described two processes of color perception without pointing out where in the visual pathway between the retina and the cortex these color interactions occur [50]. Whereas Land used binocular vision, Moutoussis et al [64] used dichoptic viewing and were able to distinguish between the two different stages of Land's color generating operations leading to color perception. They have related them to different parts of the color pathway.

By using one gray-scale image instead of a competing color, our subjects perceived an image with depth, and one in which the "colors" blend producing a color 3D image. No degradation in depth perception was measured. However, some degradation in the perception of color is evident, though the subjects still rank their color

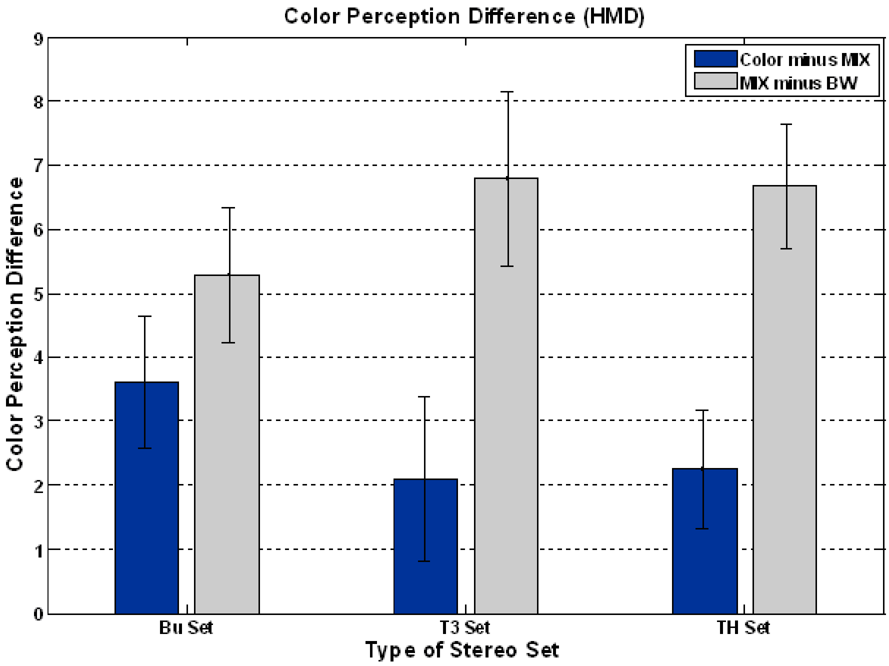


Figure 4.6: Color perception differences for all three image sets . The color difference results presented are: Color minus MIX and MIX minus BW.(a) Left group - The *Bu image set*; (b) Middle Group - The *T3 image set*; (c) Right group - The *TH image set*

perception of MIX images significantly closer to the full-color images (Col-Col), than to the gray-scale (BW-BW) images. Figure 4.7 modified from [34], portrays the information flow of the scheme that was presented to subjects (a MIX stereo pair viewed dichoptically) within the visual pathway. The images obtained from the right and left visual field are collected by the left and right retinal halves of both eyes, respectively. Each hemisphere therefore gets input from both eyes. After decussation (crossover) at the optic chiasm, color information is available to both hemispheres and the fact that the retinal image is inverted was neglected. See Section 2.1.1 for more details).

Several questions were raised by these results. First, all subjects showed a clear preference to a specific eye when viewing a MIX color stereo pair. Color perception scores were significantly higher when the color image was presented to their preferred eye. The connection between this preferred eye and the subject's dominant eye, as defined in optometric terms, will be discussed in Chapter 5. Second, the slight degradation in color perception of the MIX image raised the question of whether it may be possible to "correct" it.

The proposed approach for reducing bandwidth by using only one color camera appears to be a viable complementary approach to current techniques used in transmitting color 3D images. In addition, as will be shown in Chapter 7, reducing the resolution of one of the images does not significantly detract from the reported effect.

There are several potential shortcomings to using this approach. The most obvious, based on the presented data, is that although the hypothesis that a MIX pair will be seen in color has been validated, it is clear that the color in that scenario is less vivid than in a color pair. Furthermore, as can be seen from Figure 4.2-a there is a large variance in color perception between subjects. Thus, if a system was designed based on this approach and intended for a broad audience it may be necessary to first ascertain that the intended user is indeed among that section of the population that perceives the color more vividly rather than less. Investigation of the color degradation, variance between subjects and means for improving the color perception score will be explored in future work.

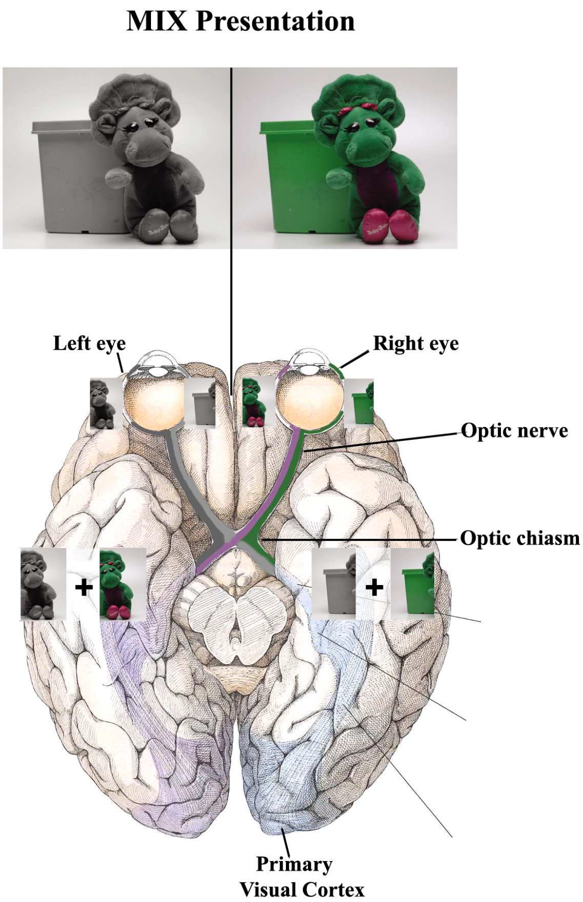


Figure 4.7: The Visual Pathway of MIX stereo Image: From eyes to primary visual cortex.

Chapter 5

Asymmetric Color Effect in Stereoscopic Viewing of MIX stereo images

In Chapter 4 we reported that when a color and a gray-scale image are viewed dichoptically, fusion occurs and a single color coherent percept is reported. As explained previously, both eyes are shown nearly the same stimulus in terms of feature information, which is further processed to yield a 3D colored image. A key observation, is that although the color contents are radically different between the eyes (color versus monochrome) the color image is preferred over the gray-scale image, producing a color perception.

During the experiments, the question of symmetry in the color perception of the MIX stereo pairs was investigated. The observers' reports of color perception seemed to be a function of the eye to which the color image was presented

The goal, in this part of the work, is to study whether the color perception of a MIX stereo pair is asymmetric between the two eyes and how this asymmetry relates to the "classical" definition of a dominant eye.

Ocular dominance, also referred to as eye dominance, is the tendency to prefer visual input from one eye over the other [72]. A recent study has argued that the visual and the oculomotor function of the dominant eye, defined by the usual criteria such as asymmetry in acuity, rivalry or sighting, is unknown. Following an extensive literature review, the authors concluded that the sighting-dominant eye,which is the eye used for monocular tasks, seems to have no unique functional role in vision [62].

We wanted to validate the hypothesis that there is asymmetry in color perception while viewing MIX stereo. Meaning a difference in the perception of color between the two eyes that depends solely on which eye is viewing the color image. In addition we wanted to examine the questions of whether the dominant eye has any influence on fusion ability, and on depth or color perception in tasks involving chromatic asymmetry between the two eyes.

Controlled psychophysical experiments were conducted in order to validate the hypothesis of the existence of asymmetry. A majority of the subjects participating in the experiment (11 of the 15 subjects) showed a clear preference to one specific eye when viewing a MIX color stereo pair. Color perception scores were significantly higher when the color image was presented to the observer preferred eye.

This chapter describes the experiments that were conducted, their results and conclusions concerning asymmetric effects of stereoscopic viewing of MIX stereo image.

5.1 Related Work

Although the brain is anatomically symmetric, the two hemispheres do not function identically. This difference in the way the two hemispheres work is called *Functional Asymmetry*. This phenomenon is widely reported in the literature [14, 92, 37, 36]. A review of hemispheric asymmetries in visual and auditory perception is summarized in [37] and a review of structural and functional asymmetry in the human brain in a historical perspective is presented by Hugdahl in [36].

The dominance phenomenon is a topic that has received considerable attention in recent years [62]. Eye dominance is defined as the tendency to prefer visual input from one eye over the other [72] and most people are grouped into either the left - or the right eye-dominant category. Mapp, Ono and Barbeito examined a set of implicit and explicit claims about the visual function of the dominant eye that have been raised over the years, since the first half of the century up to 2003. They suggest that the dominant eye has no unique functional role in vision. [62, 67]. Several criteria by which eye dominance is to be defined have been identified in the literature [15, 33] but the eye that has been identified by the different criteria as the dominant eye has not necessarily been the same. Our method of determining eye dominance is a check that determines what is known as the "sighting dominant eye". In sighting tasks, such as pointing or aiming a gun, for instance, subjects are required to align just one eye with the target and ignore visual input from the other eye. The eye that is being chosen for this task is called "the sighting dominant eye". Most subjects show consistent ocular dominance in such sighting tasks [15, 63].

5.2 Experimental Procedure

The set of experiments described here tested the hypothesis of asymmetry by the use of a PC controlled HMD (see Section 3.2 for details). These experiments were performed on 15 subjects (10 males and 5 females) between the ages of 21 and 43. All subjects were clinically tested as described in Section 3.4.1. In addition to these eye tests, hand and eye dominance was checked for all subjects. Eye dominance was defined by using the standard "hole in card" technique also known as the "Dolman method" at a distance of 4 meters. This technique is an either-or forced choice method. The subject is given a card with a small hole in the middle, and is instructed to hold it with both hands, and view a distant object through the hole with both eyes open. Although both eyes are open, only one eye can see the target. The subject intuitively chooses one eye with which the target is viewed. The observer then alternates closing his eyes or slowly draws the opening back towards his head to determine which eye is viewing the object. This eye is termed the dominant eye. In all instances, repeated trials of eye dominance resulted in the same choice, thereby confirming the results. Nevertheless, since several criteria for eye dominance exist in the literature [15, 33], this eye test is only said to have determined the "sighting dominant eye". Handedness, dominant hand, was defined as the hand that subjects prefer to write with (right or left hand).

Three sets of stereo image pairs were used. The first set of stereo images (Figure 3.8) will be referred to as *T3 image set*, the second set (Figure 3.9) will be referred to as *TH image set* and the third set (Figure 3.10) will be referred to as *Bu image set*.

In each set, four different combinations of image pairs were used (Col-Col, Col-BW, BW-Col, BW-BW) (as described in Section 3.3.3). A total number of 12 stimuli were presented in random order; each stimulus was presented ten times. Subjects were asked to rate their depth and color perception on a scale of 1 to 10 (Detailed in Section 3.4.2).

5.3 Results

Of the 15 subjects, 13 subjects were able to fuse and view all three image sets. The other two subjects successfully fused 2 of the 3 sets (subject No 7 and subject No 15). Their inability to fuse was not related to a specific image combination (MIX, BW-BW or Col-Col). Each of the stereo combination was viewed ten times. As in the previous study, all subjects reported a strong perception of depth and color in the MIX presentations. During the experiments, most of the subjects showed a clear preference to a specific eye when viewing a MIX stereo pair. Color perception scores were higher when the color image was presented to their preferred eye.

The results support the hypothesis that a color asymmetry exists in color perception of the MIX images.

Figure 5.1, presents the color perception results of the subject with the highest significance for right eye color dominance, Figure 5.2 presents the results of the subject with the highest significance for left eye color dominance and 5.3 presents the color perception results of the subject with the highest significance for no color dominance.The figures present the mean of the color perception scores for each image set, as obtained from the two MIX combinations (Col-BW and BW-Col). The X-axis separates the two MIX combinations (Col-BW and BW-Col). The Y-axis denotes the color perception score on the scale of 1–10 described earlier.

As can be seen in these figures and as was also reported by the subjects, there is a substantial difference in the color perception score between both MIX combinations. In each figure, eight bars are presented, divided into two groups of four. The left hand side group represents the results for MIX images with the color image presented to the right eye, and the right group represents the results for MIX images with the color image presented to the left eye. Three out of the four bars within a group show the color perception result obtained for each of the three image sets separately (an average of 10 trails) and the forth bar shows the average result over all 30 trials of all image sets (marked "mean"). Table 5.2 presents the mean and Std. of the color perception for both MIX pairs: BW-Col and Col-BW for each subject.

A *t-test* for independent samples was conducted separately for each one of the

15 participants, in order to compare between the color perception of MIX images with color presented on the right hand side (BW-Col) with that of MIX images with color presented on the left side (Col-BW). The data were combined from all three image sets on an overall of 30 trials per subject (except for subject No 15 and subject No 7 that have 20 trials each). The *t-test* revealed that for 2 out of 15 participants there was a significant preference for color on the left within the MIX pair, for 9 subjects color perception was significantly higher when the color image was presented on the right and for four subjects there was no significant difference. The Table presented in 5.1 summarizes the results of the paired samples tests. A binomial test indicated that the difference in number of subjects with right and left dominance for color perception was marginally significant ($p = 0.065$). Indicating that there is a preference to MIX images where the color image is presented on the right side.

Next, we tested whether side dominance for color perception is associated with the dominant hand (handedness) and/or the dominant eye. Each subject was labeled as right/left/None color dominance depending upon the results presented in Table 5.1. Table 5.1 presents the results of two-tailed *t-test* for paired samples. For each subject the color perception scores for Col-BW vs. BW-Col were compared. Positive *t-test* indicates color dominance of right side and negative *t-test* indicates color dominance of left side.

Subject No	**t-test**	
	t	**p (2-tailed)**
Subject No 1	-2.203	0.032
Subject No 2	-4.488	4.7e-5
Subject No 3	32.652	2.0e-37
Subject No 4	-8.101	4.38e-11
Subject No 5	2.652	0.010
Subject No 6	-3.186	0.003
Subject No 7	0.293	0.771
Subject No 8	-12.069	12.2e-15
Subject No 9	0.000	1.00
Subject No 10	-3.399	0.001
Subject No 11	-3.688	0.001
Subject No 12	-3.456	0.001
Subject No 13	-0.697	0.489
Subject No 14	-0.187	0.853
Subject No 15	-3.515	0.002

Table 5.1: The results of the paired samples tests

Table 5.3 presents the sample distribution by color side dominance and eye dominance.Table 5.4 presents the sample distribution by color side dominance and hand dominance.

Two separate *Cramér's X* tests [86], one between color-side dominance (left/right/no dominance) and hand dominance (left/right) and the other between color-side dominance (left/right/no dominance) and eye dominance (left/right) were conducted. (*Cramér* test examines the level of association between two categories of variables).

The analysis revealed a marginally significant association between color-side dominance and eye dominance (*Cramér's* $V = 0.618$, $p = 0.057$), such that there was tendency for subject with right sighting dominant eye to have also a right color dominant eye (and vice versa). Inspection of Table 5.3 reveals a positive association between color side and eye dominance, such as subject with right sighting dominant eye will more likely to have right color dominant eye (and vice versa).

Moreover, the analysis for color dominance and hand dominance revealed a significant association between these two variables (*Cramér's* $V = 0.68$, $p = 0.031$). This is also evident from the results themselves: Whereas one subjects with left side dominance for color perception had a left dominant hand, all of the subjects with right eye dominance for color perception had a right dominant hand. Inspection of Table 5.4 indicates a positive association between color side and hand dominance.

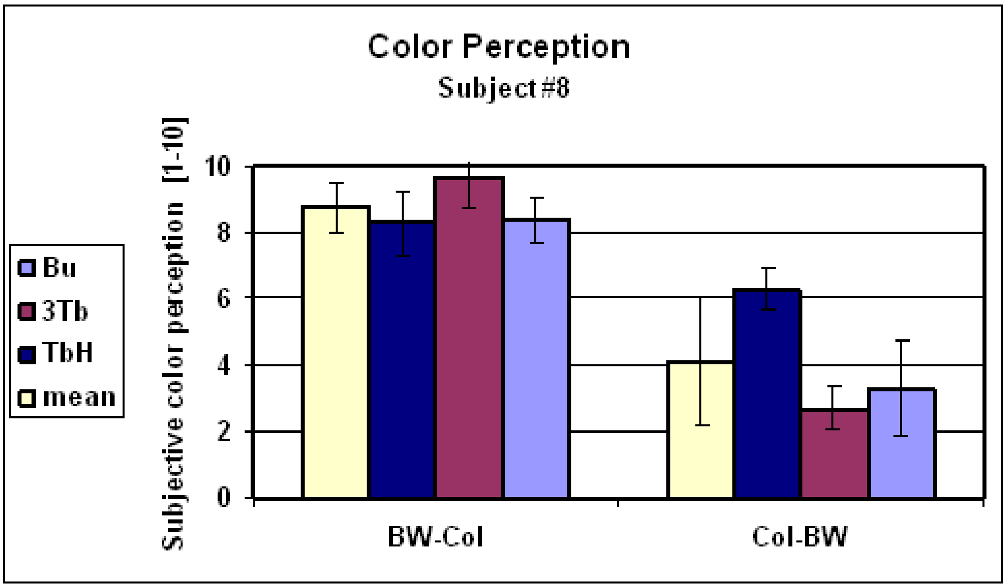


Figure 5.1: Right color dominance - Color perception of MIX images (subject No 8)

5.4 Conclusions

Out of the 15 subjects, 13 subjects were able to fuse and view all three stimuli, and the other two subjects successfully fused 2 of the three image sets. Each image set was viewed ten times. In agreement with our earlier results [93] all subjects reported a strong perception of depth and color in the MIX presentations. The two variations of MIX combinations (Col-BW and BW-Col) yielded different color scores in a majority of the subjects and trial types, with one eye appearing to be dominant for color. When all three stimuli types scores are combined, 11 of the 15 subjects showed a significant preference for one eye over the other. That is, the color was

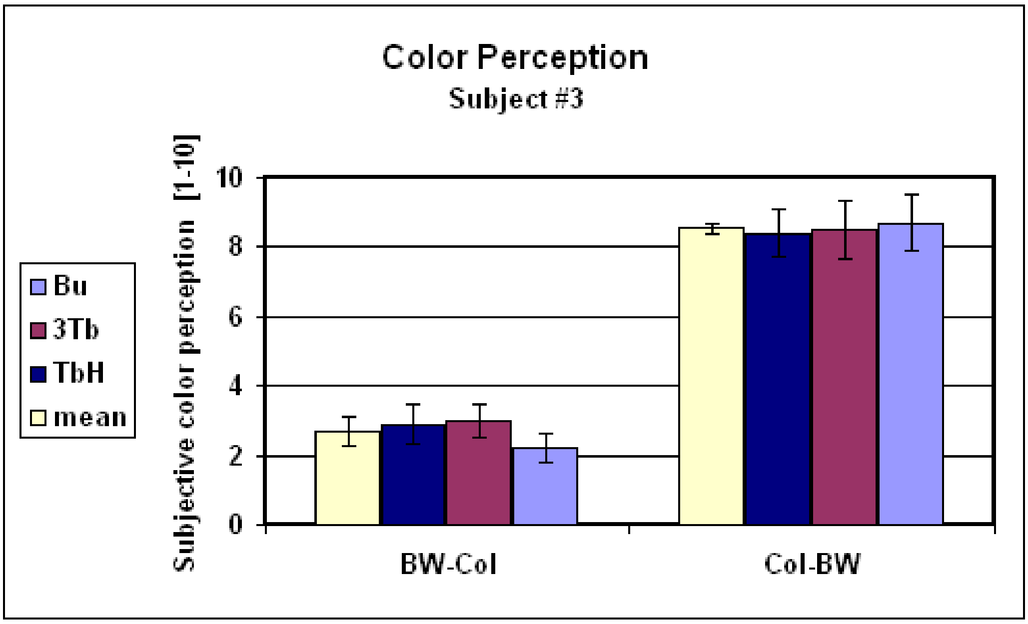


Figure 5.2: Left color dominance - Color perception of MIX images (subject No 3)

significantly more vivid when shown to that eye than when shown to the other eye. These results show an asymmetry in color perception. In other words, color, which theoretically should be side indifferent, still has a preferred side.

In addition positive association between color side and hand dominance and between color side and hand dominance color dominance were found.

However, these later findings should be taken with caution because of the relatively small sample. Future research should further investigate if this is an evidence for a new eye dominance criteria.

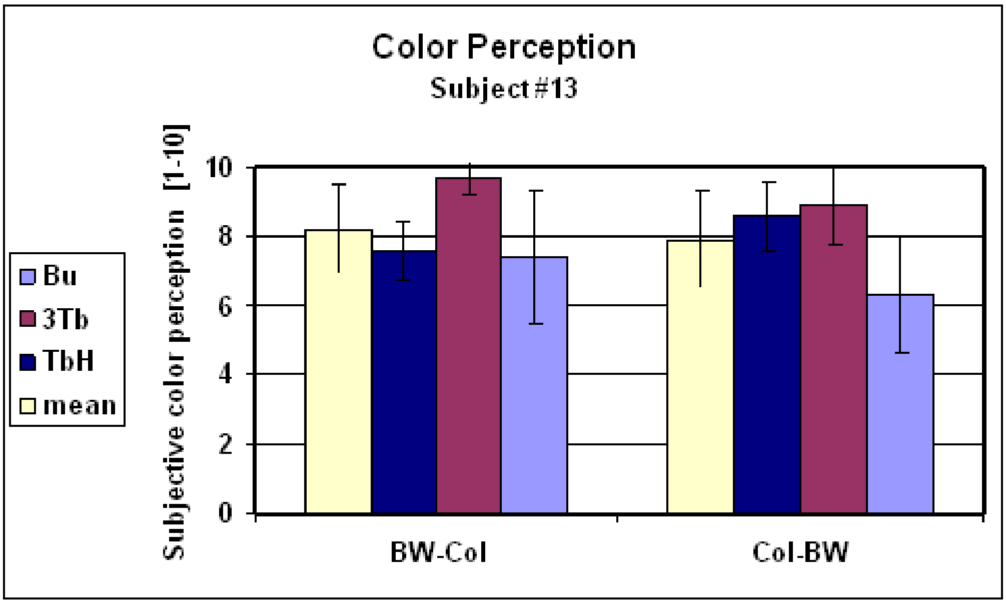


Figure 5.3: No color dominance - Color perception of MIX images(subject No 13)

Subject No.	**Color Side**	**N**	**Mean**	**Std.**
Subject No 1	Right	30	7.33	0.96
	Left	30	7.83	0.79
Subject No 2	Right	30	5.97	1.87
	Left	30	7.73	1.08
Subject No 3	Right	30	8.53	0.78
	Left	30	2.7	0.60
Subject No 4	Right	30	7.4	0.56
	Left	30	8.63	0.61
Subject No 5	Right	30	8.47	0.82
	Left	30	7.83	1.01
Subject No 6	Right	30	8.26	1.46
	Left	30	9.2	0.66
Subject No 7	Right	20	8.25	1.68
	Left	20	8.1	1.55
Subject No 8	Right	30	4.1	1.86
	Left	30	8.77	1.01
Subject No 9	Right	30	7.2	1.83
	Left	30	7.2	1.52
Subject No 10	Right	30	6.33	2.88
	Left	30	8.43	1.77
Subject No 11	Right	30	5.63	1.81
	Left	30	7.27	1.62
Subject No 12	Right	30	6.2	1.18
	Left	30	7.63	1.94
Subject No 13	Right	30	7.93	1.72
	Left	30	8.23	1.61
Subject No 14	Right	30	7.06	1.96
	Left	30	7.17	2.18
Subject No 15	Right	20	5.8	2.53
	Left	20	7.95	1.05

Table 5.2: Color perception results of MIX stereo pairs

Color Dominant Eye	Total	Sighting Dominant Eye	
		Left Eye	Right Eye
No Dominance	4	3	1
Left Color Dominant Eye	2	2	0
Right Color Dominant Eye	9	2	7

Table 5.3: Distribution by color side dominance and eye dominance

Color Dominant Eye	Total	Dominant Hand	
		Left Hand	Right Hand
No Dominance	4	0	4
Left Color Dominant Eye	2	1	1
Right Color Dominant Eye	9	0	9

Table 5.4: Distribution by color side dominance and hand dominance

Chapter 6

The Effects of Blur of MIX Images on Depth and Color Perception

This chapter mainly deals with the effects of blur on the depth and color perception of the MIX image. Images that differ in their color content (MIX image) and sharpness (blur) were presented to subjects in order to check whether fusion, rivalry or suppression occurs. Blur was introduced to one or both of the images in the MIX stereo pair. The blurring effect was achieved by applying an averaging filter with a kernel of 3X3 or 5X5 pixels to the image.

Several questions were investigated: (1) Are there any differences in depth and color perception when blurring one or both of the images in the MIX stereo pair? (2) Is there a difference in depth and color perception when blur is applied to the gray-scale image versus the color image? (3) Is color perception affected by the blurring level (3X3 or 5X5 kernel) of the image, and by which image that was blurred (color or gray-scale)?

Results show, that when blur is applied to one side of the stereo pair it merely causes a minor degradation in depth perception, in comparison to blur applied to both sides.

Moreover, results have shown that color perception improved when the gray-scale image was blurred. When the color image was blurred, color perception deteriorated. These results imply that a reduced amount of data can be presented to the gray-scale side, with minimal influence on the stereoscopic impression.

6.1 Related Work

The question of whether blurring one or both images within a stereo pair will increase or decrease stereoscopic acuity was the subject of many studies. It is known that *contrast* plays an important role in the visual system [35, 60]. Contrast, as well as the spatial frequency content of a pattern, comes into effect relatively early in the visual pathway.

A lack of contrast in an image can result in what is referred to as a *blurry image*. In terms of image processing, blurring an image can decrease contrast and attenuate high spatial frequencies. This can be introduced, for example, by a defocused lens in an Imaging system. In human vision - blurring always occurs when objects are off the horopter (the group of points in our field of view that appear to us as single image). When vision is not normal or corrected, the image can also be blurred if one or both eyes are deficient.

Several researchers [55, 54] proposed that an increase in contrast and the sharpness of contours to one eye reduces the mean dominance time for the other eye. Fahle [27] reported that low-pass filtering of the left image led to an increasing dominance of the right image (and vice versa). These results are consistent with the works of Kaplan and Blake [43, 9]. Blur apparently encourages suppression by reducing contrast sensitivity in the suppressed eye.

Suppression (as described in Section 2.1.4) is a visual condition in which the retinal image is not perceived and is mentally ignored (either partially or completely). As suggested by Lyle and Wybar [58], suppression can be caused by retinal rivalry. This is also in agreement with Simpson's [90] finding that anisometropia (one eye nearsighted and the other farsighted) can initiate blur-induced suppression. Dutour [24], translated by O'Shea [68], also speculated that rivalrous alternations can be controlled by fluctuations in the blur of one image. Since blur and contrast are correlated to stereoscopic acuity [53], reduced contrast by means of blur can cause stereoscopic acuity to degrade. Julesz [41] has shown that depth was still perceived when blurring one image within a gray-scale stereo pair, i.e., the blurred image can still be fused with the sharp image.

Blurring one image can prevent the viewing eye from contributing to high spatial frequency vision even though fusion is maintained [8]. For example, when two images that differ in sharpness and contrast are presented to a subject with normal vision, and one image has higher contrast and edge sharpness than the other, the aspect of the "weaker" image can not be reconciled with the stronger image and it is therefore suppressed [52, 78]. However, Blake et al. [12] have found that a suppressed eye is still able to contribute to stereopsis.

Reviewing these findings and studies led us to believe that reducing the resolution of one of the images in the MIX stereo pair will not impair the stereoscopic acuity to an extent that would influence depth perception abilities. Furthermore, the above studies and others [22, 21] suggest that blurring the gray-scale image in a MIX pair will facilitate the suppression of that image, thus giving a higher weight to the color image, and improving the color perception of the 3D scene. Indeed, according to our findings, blur, when applied to the gray-scale image, caused color perception scores to increase.

6.2 Experimental Procedure

The two image sets that were used in these experiments were constructed from the *Magenta image set* and *Yellow image set* (Section 3.3). The blurring of the images was achieved by further processing with a LPF (low-pass-filter) as described below. The apparatus used in these experiments was a stereoscope.

Experiments were conducted in order to test subjects' performances in such tasks, in the following manner: Subjects perceived several different combinations selected from three main groups of stereo pairs: 1) Col - Col pair: Left and right images are colored. 2) BW - BW pair: Left and right images are gray-scaled (Luminance image) 3) MIX pair: one of the images is colored and the other is gray-scale (Col - BW and BW - Col)

Each one of the three main groups was processed with a LPF in order to smooth the image, thus creating an additional sub-division of the above three chromatic groups. A simple form of spatial averaging was applied to the images, with a kernel of 3X3 or 5X5. Such an averaging filter can reduce visible noise and contrast in the image but it also flattens the texture patterns and attenuates the high spatial frequencies. This leads to a loss of details and to an unsharp and blurred image. Figures 6.1, 6.2, 6.3, 6.4, present the left and right color and gray-scale images of the *Yellow blurred image set* and Figures 6.5, 6.6, 6.7, 6.8, present the left and right color and gray-scale images of the *Magenta blurred image set.* These figures include three sub-images each. Sub-images a,b,c present the original, blurred 3X3, and blurred 5X5 color image, respectively, for the colored and gray-scale image.

(a) Full resolution image(Col) (b) Image after blur 3X3(Col3) (c) Image after blur 5X5(Col5)

Figure 6.1: The *Yellow blurred image set*: Left color images

(a) Full Resolution Image(BW) (b) Image after Blur 3x3(BW3) (c) Image after Blur 5x5(BW5)

Figure 6.2: The *Yellow blurred image set*: Left gray-scale images

The first group (Col-Col) contained 7 combinations as follows :

(a) Full resolution image(Col) (b) Image after blur 3X3(Col3) (c) Image after blur 5X5(Col5)

Figure 6.3: The *Yellow blurred image set*: Right color images

(a) Full resolution image(BW) (b) Image after blur 3X3(BW3) (c) Image after blur 5X5(BW5)

Figure 6.4: The *Yellow blurred image set*: Right gray-scale images

- Col-Col - The reference colored pair in which the left and right images are colored and have full resolution.
- Col3-Col - a colored pair in which the left image is blurred with the 3X3 kernel. The right image is in full resolution.
- Col-Col3 - a colored pair in which the right image is blurred with the 3X3 kernel. The left image is in full resolution.
- Col3-Col3 - a colored pair in which the left and right images are both blurred with the 3X3 kernel.
- Col5-Col - a colored pair in which the left image is blurred with a 5X5 kernel. The right image is in full resolution.
- Col-Col5 - a colored pair in which the right image is blurred with a 5X5 kernel. The left image is in full resolution.

(a) Full resolution image(Col) (b) Image after blur 3X3(Col3) (c) Image after blur 5X5(Col5)

Figure 6.5: The *Magenta Blurred image set*: Left Color images

(a) Full resolution image(BW) (b) Image after blur 3X3(BW3) (c) Image after blur 5X5(BW5)

Figure 6.6: The *Magenta Blurred image set*: Left gray-scale images

- Col5-Col5 - a colored pair in which both images are blurred with a 5X5 kernel.

Each one of the colored images (left and right) was also converted to a gray-scale image (see section 3.3). By applying the same blurring masks (3X3 and 5X5) to the gray-scale image, 7 more combinations were created, out of the second (BW-BW) group:

- BW-BW - The reference gray-scale pair in which the left and right images have no chromatic content and are in full resolution.

- BW3-BW - a gray-scale stereo pair containing two images with the no chromatic content, the left image is blurred with a 3X3 kernel. The right image is in full resolution.

- BW-BW3 - a gray-scale stereo pair containing two images with the no chromatic content, the right image is blurred with a 3X3 kernel. The left image is in full resolution.

(a) Full resolution image(Col) (b) Image after blur 3X3(Col3) (c) Image after blur 5X5(Col5)

Figure 6.7: The *Magenta Blurred image set*: Right color images

(a) Full resolution image(BW) (b) Image after blur 3X3 (BW3) (c) Image after blur 5X5 (BW5)

Figure 6.8: The *Magenta Blurred image set*: Right gray-scale images

- BW3-BW3 - a gray-scale stereo pair containing two images with the no chromatic content, both right and left images are blurred with a 3X3 kernel.
- BW5-BW - a gray-scale stereo pair containing two images with the no chromatic content, the left image is blurred with a 5X5 kernel. The right image is in full resolution.
- BW-BW5 - a gray-scale stereo pair containing two images with the no chromatic content, the right image is blurred with a 5X5 kernel. The left image is in full resolution.
- BW5-BW5 - a gray-scale stereo pair containing two images with the no chromatic content, both right and left images are blurred with a 5X5 kernel.

The MIX group (Col-BW, BW-Col) differ in the position of the colored image within the pair: color on the right side or on the left side. 18 more combinations were created. The third group of MIX pairs with a colored right image and gray-scale left image contained the following types:

- BW-Col - a MIX pair with a left gray-scale image and a right colored image. Both images are in full resolution " BW - Col3 - a MIX pair with a right colored image and a left gray-scale image. The right colored image is blurred with a 3X3 kernel and left image is in full resolution.
- BW - Col5 - a MIX pair with a right colored image and a left gray-scale image. The right colored image is blurred with a 5X5 kernel and left image is in full resolution.
- BW3-Col - a MIX pair with a left gray-scale image and a right colored image. The left gray-scale image is blurred with a 3X3 kernel. The right image is in full resolution.
- BW3 - Col3 - a MIX pair with a right colored image and a left gray-scale image. The right and left images are both blurred with a 3X3 kernel.
- BW3 - Col5 - a MIX pair with a right colored image and a left gray-scale image. The left gray-scale image is blurred with a 3X3 kernel and the right color image is blurred with 5X5 kernel.
- BW5-Col - a MIX pair with a left gray-scale image and a right colored image. The left gray-scale image is blurred with a 5X5 kernel. The right colored image is in full resolution.
- BW5-Col3 - a MIX pair with a left gray-scale image and a right colored image. The right image is blurred with a 3X3 kernel and the left image is blurred with 5X5 kernel.
- BW5-Col5 - a MIX pair with a left gray-scale image and a right colored image. The both right and left images are blurred with a 5X5 kernel.
- Col-BW - a MIX pair with a right gray-scale image and a left colored image. Both images are in full resolution
- Col3 -BW - a MIX pair with a right gray-scale image and a left colored image. The left colored image is blurred with a 3X3 kernel. The right gray-scale image is in full resolution.
- Col5 -BW- a MIX pair with a right gray-scale image and a left colored image. The left colored image is blurred with a 5X5 kernel. The right gray-scale image is in full resolution.
- Col - BW3 - a MIX pair with a left colored image and a right gray-scale image. The right gray-scale image is blurred with a 3X3 kernel. The left image is in full resolution.
- Col3 - BW3 - a MIX pair with a left colored image and a right gray-scale image. Both right and left images are blurred with a 3X3 kernel.

- Col5 - BW3 - a MIX pair with a left colored image and a right gray-scale image. The left image is blurred with a 5X5 kernel. The right image is blurred with 3X3 kernel.
- Col -BW5 - a MIX pair with a left colored image and a right gray-scale image. The right gray-scale image is blurred with a 5X5 kernel. The left colored image is in full resolution
- Col3 - BW5 - a MIX pair with a left colored image and a right gray-scale image. The right gray-scale image is blurred with 5X5 kernel and the left colored image is blurred with a 3X3 kernel.
- Col5 - BW5 - a MIX pair with a left colored image and a right gray-scale image. Both right and left image is blurred with a 5X5 kernel.

The table presented in Figure 6.9 summarizes the properties of the left and right images of the different stimuli that were used in the experiments. The column headed *Chromatic Content* divide the stimuli into four main groups as described earlier: gray-scale, colored and two types of MIX images. The column headed *Card Name* assigns each stereo pair with a label for easy reference. The columns headed *Left eye/Right eye* presents information about the Color Content and the Blur in the image presented to each eye. The column headed *Color Content* specifies whether the image is gray-scale (BW) or color (Col). The column headed *Blur* describes the amount of blur applied to the image (No - for no blur, 3X3 and 5X5).

The total number of stimuli used in this experiment was 32 for each of the image sets (a total of 64 stimuli). Each stimulus was presented twice. Except for a few instances, all subjects viewed each of the 64 stimuli twice.

subjects. These experiments were performed on 20 subjects (10 males and 10 females) between the ages of 20 and 45. All subjects were clinically tested. Details of the general experiment protocol are presented in Section 3.4.1.

For each image pair, subjects were asked to rate their color perception on a scale of 1 to 10, with 1 denoting a gray-scale image and 10 an image in vivid colors. They were also asked to rate the depth perception from 1 to 10, with 1 corresponding to a flat image with no depth at all and 10 to a full 3D image .

6.3 Results

6.3.1 Depth Perception of MIX Images Under Blurring Conditions

Figures 6.10, 6.11, 6.12, present the depth perception results by color combination (BW-BW, Col-Col, MIX) for each of the blurred image sets, respectively. Inspection of the graphs reveal a moderate degradation in depth perception with blur level. However because all depth scores ranged between a a minimum of 8.3 to to 9.9 on a 1 to 10 scale, indicating a possible ceiling effect, statistical analysis were not performed. Results show, that when blur is applied to one side of the stereo pair the degradation in depth perception is minor, in comparison to blur applied to both sides.

6.3.2 Color Perception of MIX Images Under Blurring Conditions

The following analysis were conducted to test whether blur of the gray-scale image affect color perception differently than blur of color image. Table 6.1 summarizes the mean and Standard Deviation (Std.) of the color score differences between the MIX pair and the gray-scale pair (MIX minus BW) and the color score differences between the full color pair and MIX pair (Color minus MIX) by blur level ("No", 3X3, 5X5).

Magenta Image Set		
Color Difference	**Mean**	**Std.**
Col minus MIX	3.05	1.27
Col minus MIX3	2.25	1.23
Col minus MIX5	1.45	1.18
MIX minus BW	5.78	1.15
MIX3 minus BW	6.58	1.24
MIX5 minus BW	7.39	1.23

Yellow Image Set		
Color Difference	**Mean**	**Std.**
Col minus MIX	1.602	0.94
Col minus MIX3	0.85	0.82
Col minus MIX5	0.69	0.76
MIX minus BW	7.25	0.93
MIX3 minus BW	8.0	0.84
MIX5 minus BW	8.17	0.78

Table 6.1: Color perception difference by image set (stereoscope). Means and Standard Deviation (Std.) of color perception difference for both Magenta and Yellow blurred image sets

The color score differences were calculated for each of the two stereo sets separately. Two-way ANOVAs for repeated measures were conducted separately for the magenta and yellow image image sets on the color difference scores with type of difference (MIX minus BW, Color minus MIX) and blur level ("No", 3x3, 5x5) as within subjects variables.

Results have shown that the difference in color perception between the Col-Col pair and the MIX pair (Color minus MIX) increase with the amount of blur, for both the magenta and yellow image set as indicated by the significant interactions between type of difference and blur level).(F(2,18)=32.12, $p = 1.15e-6$), (F(2,15)=16.39, $p = 0.00016$) for the Yellow and Magenta image set respectively).

The Tables presented in 6.2 summarizes the Means and Standard Deviations of color perception by blur level (3X3, 5X5), type of image to be blurred (color, gray-scale) for both image sets. A two way ANOVA for repeated measures conducted on these data separately for each image set, revealed that the blurring effect is significantly larger for the MIX stereo pair with blurred gray-scale image (M=7.94) than the MIX stereo pair with blurred color image (M=4.01) (F(1,19)=120.15, $p = 1.17e-9$) for the magenta image set. Similar results were obtained for the yellow image set ((M=9.08) for the colored image (M=4.38) for the gray-scale image) (F(1,19)=183.28, $p = 3.5e-10$) .

Magenta Image Set		
Stereo Pair	**Mean**	**Std.**
BW3-Col	6.42	2.12
BW-Col3	3.71	1.61
BW5-Col	7.89	1.78
BW-Col5	2.77	1.59
Col-Bw3	8.58	1.17
Col3-BW	5.16	1.76
Col-Bw5	8.84	1.39
Col5-BW	4.21	1.62

Yellow Image Set		
Stereo Pair	**Mean**	**Std.**
BW3-Col	8.77	1.28
BW-Col3	4.71	1.56
BW5-Col	8.83	1.13
BW-Col5	3.19	1.29
Col-Bw3	9.34	0.85
Col3-BW	5.67	1.77
Col-Bw5	9.60	0.42
Col5-BW	3.66	1.77

Table 6.2: Means and Standard Deviations of color perception by blur level (3X3,5X5) and type of image to be blurred color,gray-scale

The Tables presented in Figure 6.13 summarizes the Means and Standard Deviation of color perception by experimental conditions, separately for each image set.

Figures 6.14(a) and 6.14(b) present the color perception as was obtained from the *Yellow image set* when blurring the color image and the gray-scale image, accordingly.

For each blur level the results shown are an average over both MIX pair combinations (Col-BW, BW-Col).The X-axis represents the blur level ("No",3X3,5X5), from "No blur" on the left side to a blur level of 5X5 on the right side. The Y-axis denotes the color perception score on the scale of 1–10 described earlier. As can be seen from both figures, color perception increases with blur level, when blur is applied to the gray-scale image Figure 6.14(b) and decreases with blur level when blur is applied to the colored image Figure 6.14(a). Similar results were obtained for the *Magenta image set* presented in Figures 6.15(a), 6.15(b), when blurring the color image and the gray-scale image, accordingly.

Based on these findings Chapter 7 deals only with compression of the gray-scale image within the MIX pair.

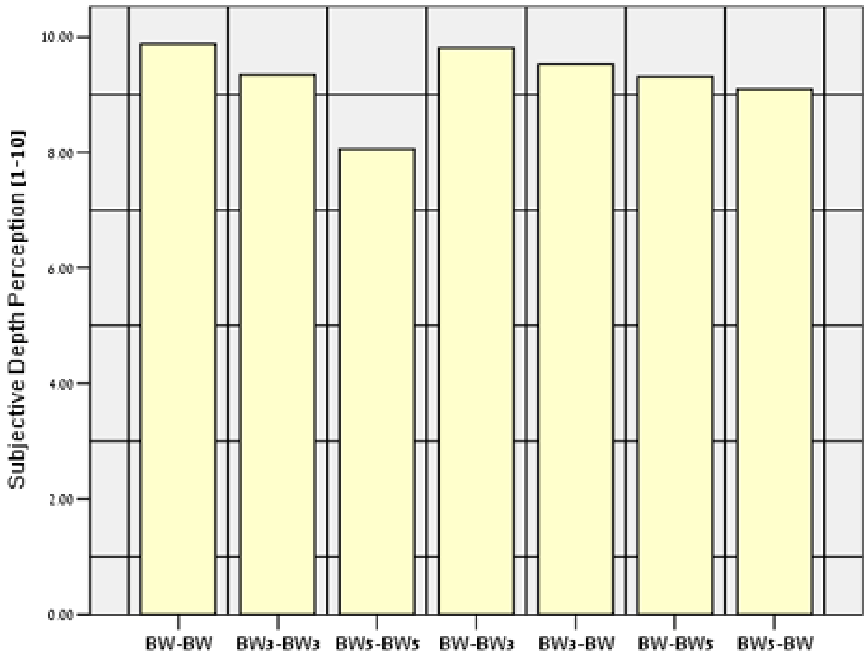
6.4 Conclusions

The most straightforward means for influencing the predominance of the color image over the gray-scale image is to vary some aspects of the competing stimuli. These manipulations are described in the literature with variables as contrast, luminance, contour density, frequency, size etc. [11].

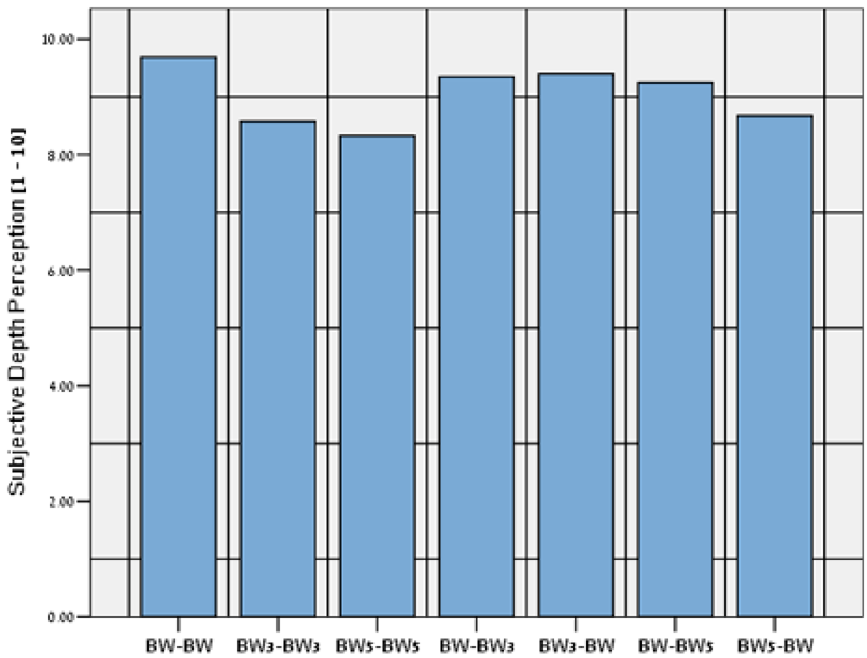
The results reported in this Chapter reveal that color perception of MIX stereo pair can be further improved when the gray-scale image is blurred while depth stay merely intact. Moreover,this implies that the amount of data in the gray-scale image can further be reduced. These finding is the basis for further investigation on the subject of compression that is described in Chapter 7.

Chromatic Content	Card Name	Left Eye		Right Eye	
		Color Content	Blur	Color Content	Blur
Gray-Scale Pairs	BW - BW	BW	No	BW	No
	BW3 - BW	BW	3 X 3	BW	No
	BW – BW3	BW	No	BW	3 X 3
	BW3 – BW3	BW	3 X 3	BW	3 X 3
	BW5 - BW	BW	5 X 5	BW	No
	BW – BW5	BW	No	BW	5 X 5
	BW5 – BW5	BW	5 X 5	BW	5 X 5
Color Pairs	Col - Col	Color	No	Color	No
	Col3 - Col	Color	3 X 3	Color	No
	Col – Col3	Color	No	Color	3 X 3
	Col3 – Col3	Color	3 X 3	Color	3 X 3
	Col5 – Col	Color	5 X 5	Color	No
	Col – Col5	Color	No	Color	5 X 5
	Col5 – Col5	Color	5 X 5	Color	5 X 5
MIX Pairs (Color presented to the right eye)	BW - Col	BW	No	Color	No
	BW – Col3	BW	No	Color	3 X 3
	BW – Col5	BW	No	Color	5 X 5
	BW3 - Col	BW	3 X 3	Color	No
	BW3 – Col3	BW	3 X 3	Color	3 X 3
	BW3 – Col5	BW	3 X 3	Color	5 X 5
	BW5 - Col	BW	5 X 5	Color	No
	BW5 – Col3	BW	5 X 5	Color	3 X 3
	BW5 – Col5	BW	5 X 5	Color	5 X 5
MIX Pairs (Color presented to the left eye)	Col - BW	Color	No	BW	No
	Col3 - BW	Color	3 X 3	BW	No
	Col5 - BW	Color	5 X 5	BW	No
	Col – BW3	Color	No	BW	3 X 3
	Col3 – BW3	Color	3 X 3	BW	3 X 3
	Col5 – BW3	Color	5 X 5	BW	3 X 3
	Col - BW5	Color	No	BW	5 X 5
	Col3 – BW5	Color	3 X 3	BW	5 X 5
	Col5 – BW5	Color	5 X 5	BW	5 X 5

Figure 6.9: The stimuli presented in the blur experiments

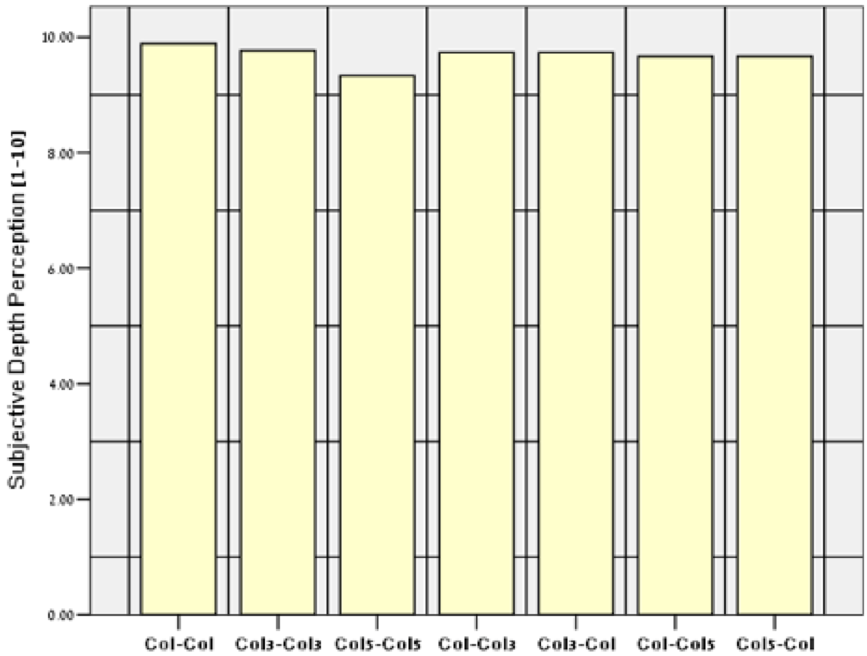


(a) Depth perception in the *Yellow Blurred image set* (BW-BW)

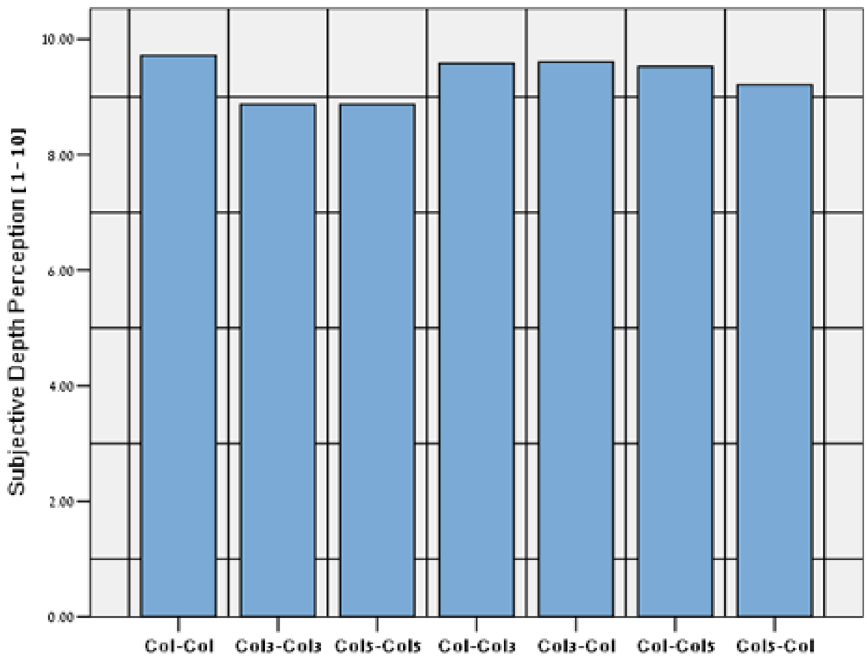


(b) Depth perception in the *Magenta Blurred image set* (BW-BW)

Figure 6.10: Depth perception of blurred gray-scale stereo pairs

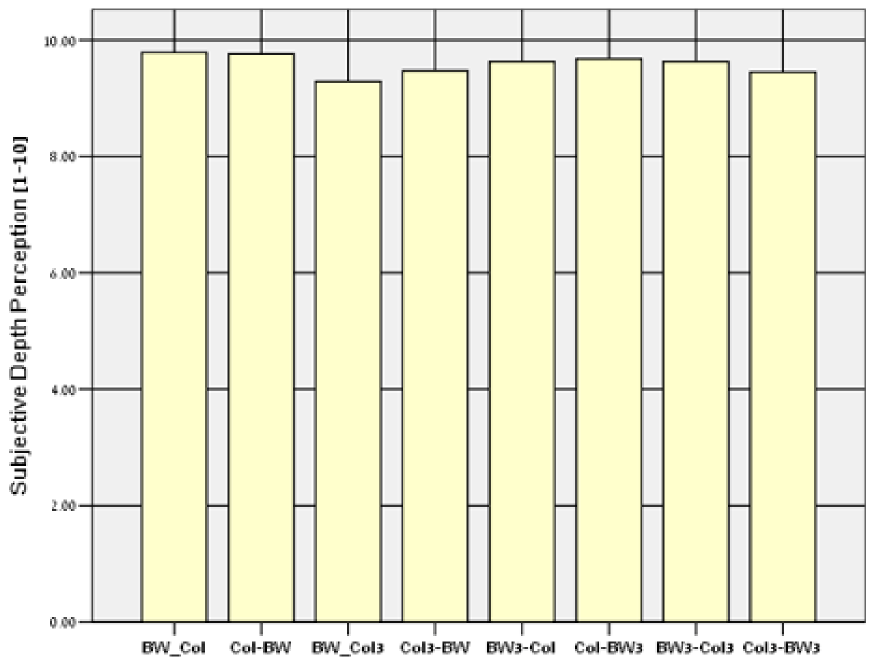


(a) Depth perception in the *Yellow Blurred image set* (Col-Col)

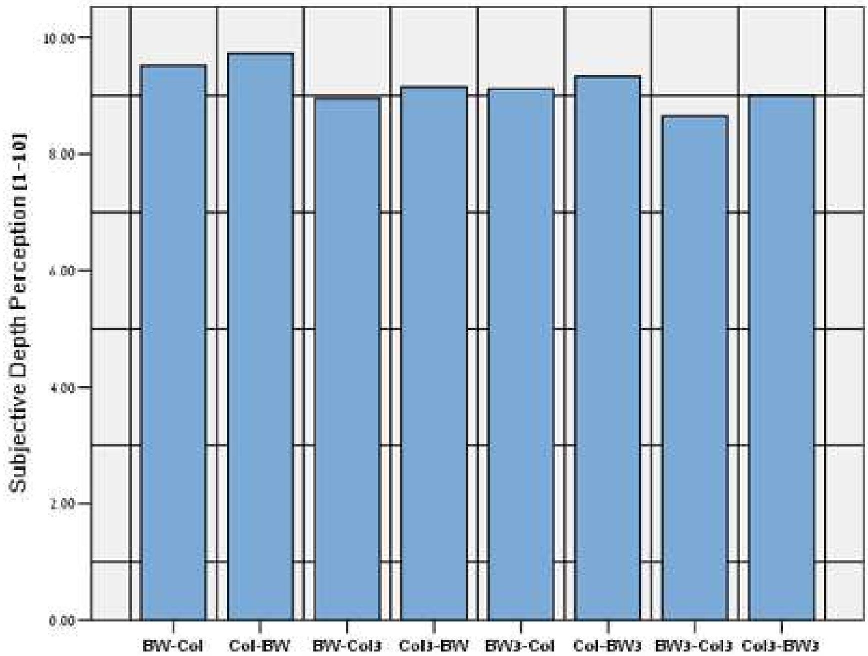


(b) Depth perception in the *Magenta Blurred image set* (Col-Col)

Figure 6.11: Depth perception of blurred colored stereo pairs



(a) Depth perception in the *Yellow Blurred image set*(MIX)



(b) Depth perception in the *Magenta Blurred image set* (MIX)

Figure 6.12: Depth perception of blurred MIX stereo pairs

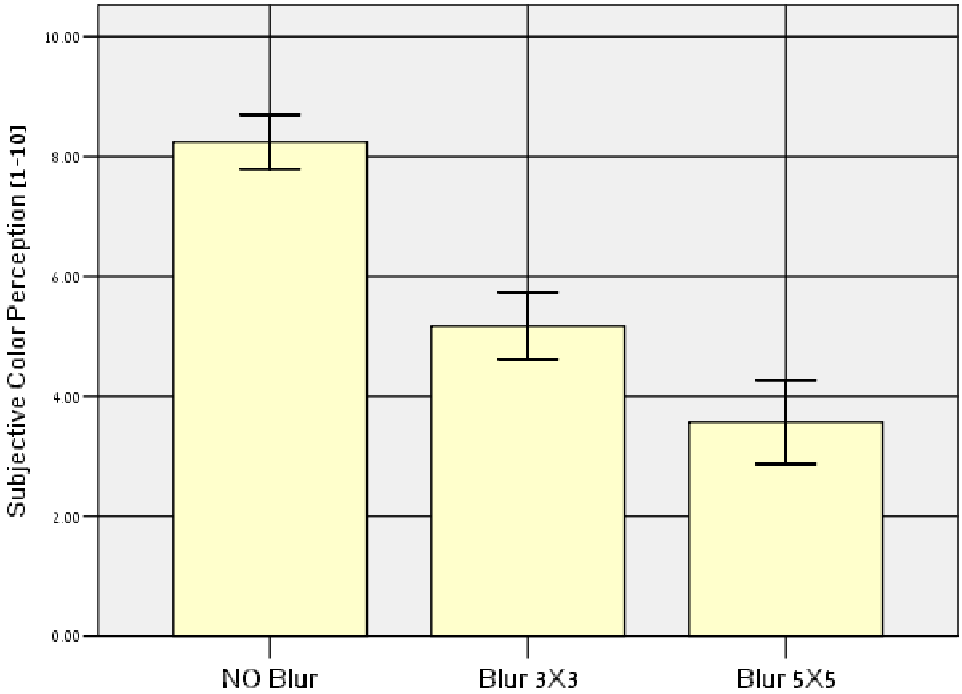
YELLOW SET		Color Image Side			
		Left		Right	
		Blurred Color Image	Blurred BW Image	Blurred Color Image	Blurred BW Image
Blur Level					
3X3					
	Mean	5.5625	8.6875	4.8438	9.2500
	Std. Deviation	1.87861	1.30224	1.57817	0.91287
5X5					
	Mean	3.7188	8.8229	3.3438	9.5000
	Std. Deviation	1.83456	1.35054	1.46877	0.48305

(a) Blur Yellow Image Set

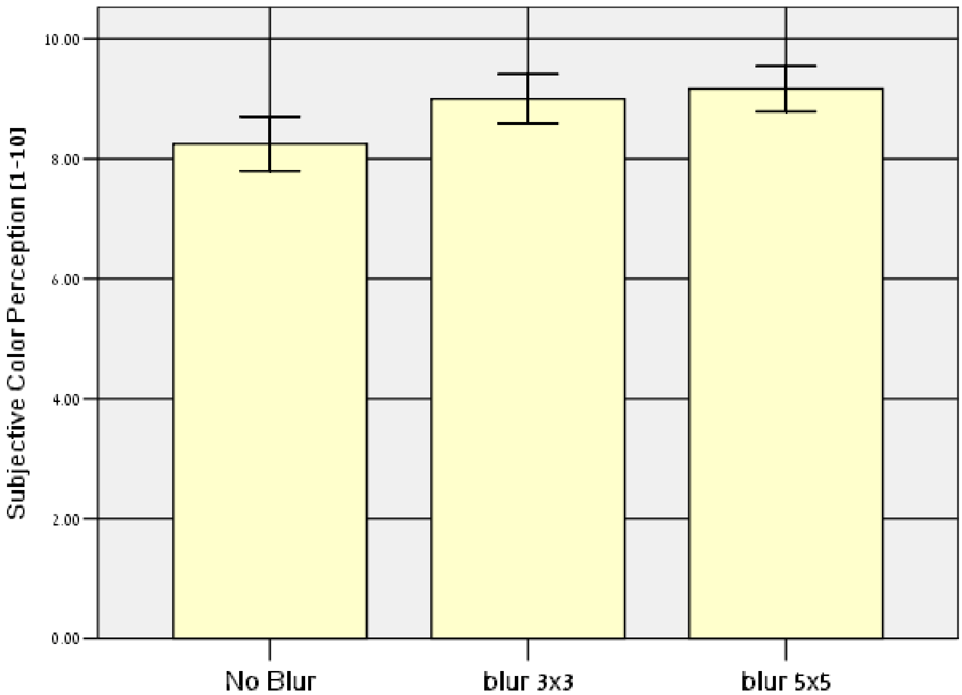
MAGENTA SET		Color Image Side			
		Left		Right	
		Blurred Color Image	Blurred BW Image	Blurred Color Image	Blurred BW Image
Blur Level					
3X3					
	Mean	5.1053	6.4298	3.7368	8.6316
	Std. Deviation	1.74467	2.18604	1.65301	1.18839
5X5					
	Mean	4.2368	7.8421	2.9737	8.8421
	Std. Deviation	1.61906	1.76425	2.08482	1.39496

(b) Blur Magenta Image Set

Figure 6.13: Means and Standard Deviation of Color perception by experimental conditions

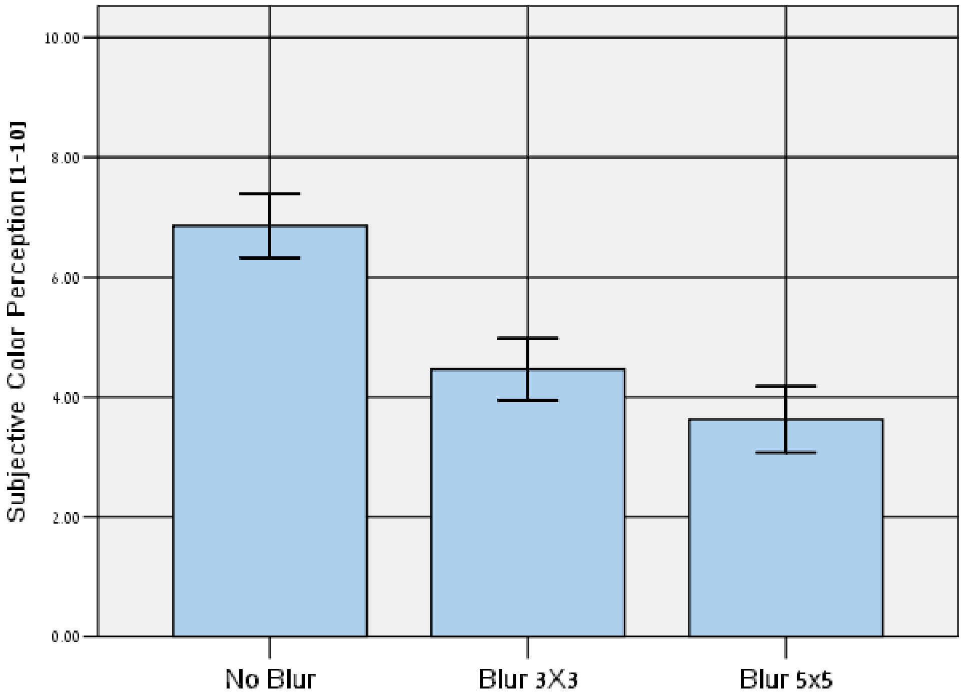


(a) Blurred color image

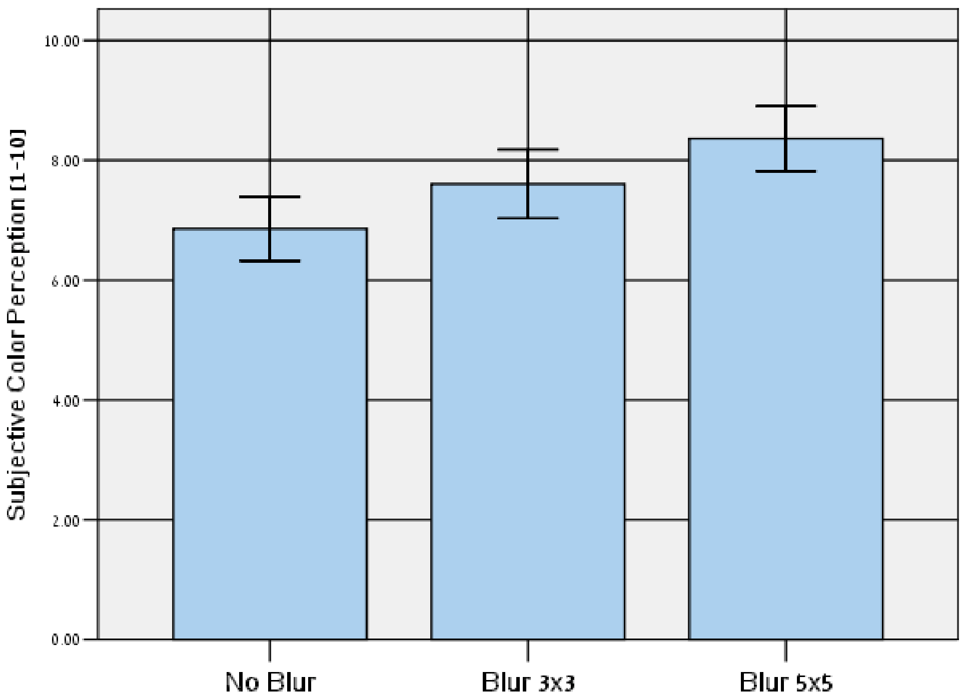


(b) Blurred gray-scale image

Figure 6.14: Color perception of the blurred Yellow image set



(a) Blurred color image



(b) Blurred gray-scale image

Figure 6.15: Color perception of the blurred Magenta image set

Chapter 7

The Effects of Compression of MIX Images on Depth and Color Perception

The research described in this dissertation explores a phenomenon that can potentially be used as a basis for a color stereo compression method which is motivated by the properties of the **Human Visual System** (HVS). The previous chapter has demonstrated that when a gray-scale image is blurred, the color perception of the MIX stereo pair improves, without impairing depth perception. It thus appears that blurring the gray-scale image contributes to the dominance of the color image over the gray-scale image. This is in agreement with other studies that were conducted on pairs of gray-scale images [41, 22, 21]. Yet, the extent to which we can further reduce the amount of data in the stereo pair needs more investigation. If fewer bits can be used in the gray-scale image, e.g., due to compression, less bandwidth is required for transmission, and less memory space is necessary for storage. This chapter compares the effect of applying three different compression methods to one of the images within a stereo pair, to achieve such further data reduction. Based on the results of Chapter 6, all the compression methods that were tested and are presented in this chapter were applied solely to the gray-scale image in the MIX pair. We conducted experiments where subjects viewed different MIX stereo pairs, compressed by three different compression techniques: Gaussian pyramid, Quantization and blurring using a low-pass filtering (LPF). Subjects were then asked to rate depth and color perception. The purpose of these tests was not to rate the compression techniques, nor address other ways to take advantage of the stereo image redundancy but rather to establish that the basic effect can endure compression of various sorts. A secondary goal was to show that the results from the previous chapter (which discussed using blurring using an LPF, viewed using a stereoscope), extend to other compression methods, and to other displays (here, an HMD). The results from the experiments show that the different compressions methods all yielded similar results to that of using LPF (blurring): The use of a reduced-information monochromatic image does not impact depth perception, and improves color perception slightly (compared to the use of a non-compressed monochromatic image). Sections 7.2 and Section 7.2, present some relevant background and related work concerning stereo redundancy and image compression, with specific reference to the aspects of the three image compression techniques that were implemented. Section 7.3 describes the experimental procedures that were used in order to test the theory of this study and Section 7.4 presents the results. Section 7.5 concludes this chapter.

7.1 Background

7.1.1 Compression and data redundancy

Image compression plays an important role in the storage and transmission of color images. A stereo color image, by nature, requires twice the amount of storage of one color image and six times the amount of storage of a single gray-scale image. Image compression refers to the process by which the amount of data used to represent an image is reduced. Our general compression scheme is presented in Figure 7.1

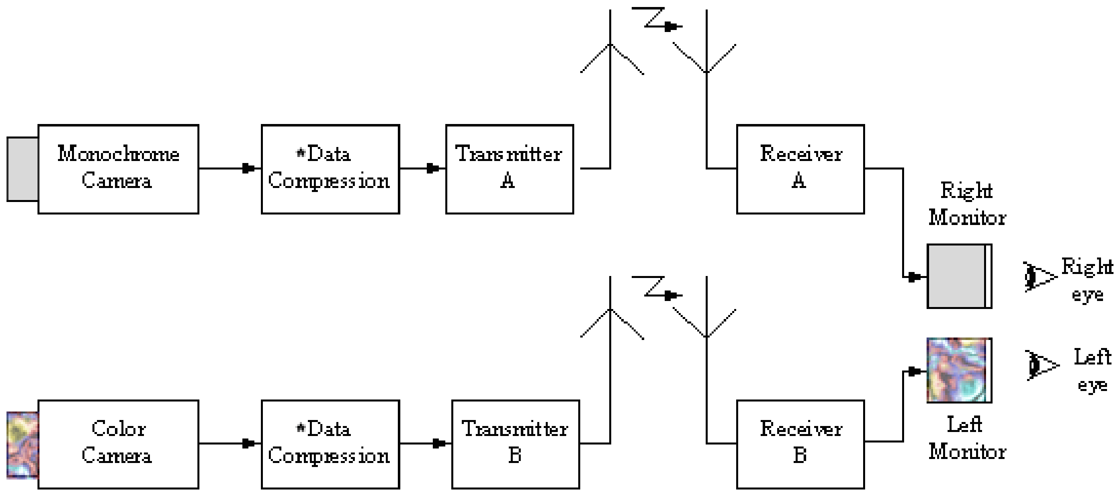


Figure 7.1: The general scheme to compression.

Compression reduces or eliminates redundant or irrelevant data from the signal. The term *redundant data* refers to the data that provides either no relevant information or information that is already known. As described earlier in Section 2.4) three basic data redundancies can be identified in image processing: *Spatial redundancy, Temporal redundancy and Psychovisual redundancy.* Data compression is achieved when one or more of these redundancies are reduced or eliminated. The potential applications of this research involve a human user. An emphasis will therefore be put on the *Psychovisual redundancy*, i.e. the redundancy that originates from the Human Visual System characteristics . An extensive overview on data redundancy can be found in [30].

7.1.2 The Human Visual System and psychovisual redundancy

The human perceptual system does not employ all of the information available from the outside world. The data that is gathered through the visual system is partial, and in order to perceive a fully detailed image, completion and perception techniques and procedures are applied to the information (e.g. shape from movement, shape from shading, etc.).

As was explained in Section 2.1.1, from the very beginning of the data collection procedure, at the transition from retinal receptors to ganglion cells, a mass reduction of information is performed, with a ratio of 1:120. In simple words, the visual path takes a very concise representation of the real visual scene, and transfers it, through the different processing areas in the brain, into a fully reconstructed perceptual image.

The amount of redundant information in a stereoscopic image is enormous. First, as was previously mentioned, there is the known redundancy within each image, expressed in correlation between nearest pixels, that is used for common single image compression techniques [30]. In addition, the similarity between the two images constructing a stereo pair can be used for further compression.

Since *Psychovisual redundancy* results from aspects of the human vision, compression algorithms that are inspired by it usually remove information that is irrelevant to human vision. Some typical examples include: *Resolution reduction.* Given an image of 1280 x 1024 pixels, image size can be reduced to 640 x 512 pixels by merging 4 neighboring pixels into to one pixel, e.g. by using the mean value. Usually, for natural images, the content will still be recognizable. The compression ratio is 1:4. *Color reduction.* A 24 bit representation of each pixel (3 color channels, 8 bit per channel) is able to represent 2^{24} colors. However, the human eye is able to distinguish between much less than that (a maximum of 350,000 different colors under optimal sunlight conditions). Reducing the number of colors to 256 (an 8 bit image) yields a compression ratio of 1:3 without a significant loss of color sensation.

High Frequency reduction The fact that the Human Visual System is less sensitive to the high frequency content of an image, is used in the JPEG compression methods [1]. Compression can be performed in both lossy and lossless manners. Lossy compression is used in order to gain higher compression at the cost of loosing some of the information in the image. Compression ratios can range from a low compression ratio of 1:4 values as high as 1:200 (depending on the image quality).

7.2 Related Work

Two of the most important parameters in the design of any vision device, and specifically a stereoscopic device, are memory size and transmission channel capacity. The doubled bandwidth requirements are prohibitive, compared to monocular color imaging, or gray-scale stereoscopic imaging. Thus, much research effort today is dedicated to the optimization and compression of a stereoscopic image in order to enable the transmission of stereo video streams over the bandwidth of a monoscopic (single-channel) channel. This has led to the proposal of various compression schemes for stereo images and stereo video streams. Various monoscopic image compression approaches have been developed, and are continually refined and improved (e.g., the JPEG family of compression standards [1]). However, while these methods can successfully reduce the bandwidth requirements of each channel, they fail to take advantage of the large redundancy that exists in stereoscopic imaging due to the fact that both channels contain information about the same objects, albeit taken from slightly different perspectives. Information about the disparity between the channels, i.e. the amount of shift one needs to perform on the pixels within one image to locate the corresponding pixels in the other image, can thus be used to further reduce the combined bandwidth requirements of the two channels. Indeed, many existing stereo compression schemes utilize the correlation between the two stereo images, the *inter-frame redundancy* [71, 97]. These methods exploit the redundancy between the two images by using disparity-compensated prediction. Such predictions depend on estimating the magnitude and direction of the disparity. Several stereo compression methods have been developed based on the concept of disparity estimation [57, 97, 99, 100]. While [97] estimate disparity based on a small block, Sethuraman et al. [79, 80, 81] present methods for stereo compression based on the concept of multi-resolution disparity estimation. A single image and a disparity map are used to synthesize a second image for the stereoscopic pair. Other methods for the compression of a stereoscopic image apply different compression strategies to each of the images separately, while using information about the disparity between the channels.

In fact, any of the techniques used in motion compensation (for example, MPEG [13, 48], that works at a block level), are applicable to disparity estimation [98]. The disparity estimation/disparity compensation approach resembles motion estimation/motion compensation methods, which are popular for video coding. Intra-frame redundancy can also be found between any two sequential image frames or between left-right 3D-stereoscopic image pairs and can be used in order to achieve significant data compression [85].

While the above methods take advantage of the *spatial* similarity between the stereo images, other methods [75] use frequency as the basis for compression, without relying on any complex calculation of disparity compensation.

Kim et al. [45] suggest a scheme for high-resolution 3D stereoscopy via monoscopic HDTV bandwidth, using three cameras. They use a monoscopic color camera to construct the "main stream", and two gray-scale low-resolution cameras to create a disparity map. The compressed disparity map is transmitted as a low-bandwidth "auxiliary stream", and a synthesized color pair is computed on the receiver end using the main and auxiliary streams. However, this method requires three synchronized cameras.

Julesz [41] has conducted some experiments on random dot stereograms. In one of his experiments the left image of a random dot stereogram was blurred by defocusing and depth perception was reported to be easily achieved. According to his findings, the stereogram was reported to be perceived as sharp image which led to the conclusion that this phenomenon is in agreement with the suppression theory as discussed in [44]. Dinstein et al. [20], motivated by the suppression theory, proposed their approach to stereo image compression: One of the stereo image retain the details of the scene while the second can be compressed and supply the additional information needed for disparity calculation. These experiments were conducted on gray-scale pairs using several techniques for the compression of the stereo pair [20, 22, 21].

According to the suppression theory, in case of binocular rivalry, one of the images is suppressed and the other image gains the attention of the visual system. The experiments conducted in this chapter are reminiscent of Distein's work, but with the added novelty of evaluating the effects of compression on a MIX stereo pair. We additionally compare the results from three different compression methods.

7.3 Experimental Procedure

According to the results presented in Chapter 6 color perception improves when the gray-scale image is blurred without having any influence on stereoscopic impression. In order to test whether perception is affected by compression of the gray-scale image within the MIX pairs, several experiments were conducted. These experiments evaluated color and depth perception when the MIX combination was further compressed.

The image sets used in these experiments was the *Bu image set*, shown in Figure 3.10. In addition to the two basic MIX combinations of the stereo pairs (Col-BW, BW-Col, as described in Section 3.3.3) six more MIX images were combined from one full resolution color image, and one compressed gray-scale image. The compression of the gray-scale images was achieved by one of three compression methods: The Gaussian Pyramid technique, Quantization and Low-Pass Filtering. (LPF). LPF, although not a compression method per se, gives a notion of relevant redundant information removed from the image.

The four sub-sets of the *Bu image set* that were used are listed in Table 7.1.

MIX image with no compression. The original left/right image was a 24 bit colored image, 1280 x 1024 pixels in size. Both MIX image are presented in Figure 7.2. The left and right color images were converted to an 8 bit gray-scale image by using the luminance channel after an L*a*b* transformation (resulting in a continuous range of gray-levels from 0 to 256). A MIX stereo pair was combined from one color image and one gray-scale image (see Section 3.3.1). These uncompressed two pairs of MIX images (Col - BW, BW- Col) served as a reference (Figure 7.2). Four combinations were presented with no compression Col - Col (full color stereo image), BW - BW (full gray-scale image) and two MIX image as described above. At a frame rate of 30 frames per second the required bit rate will be 1024 x 1280 x 8 x 3 x 30 = 943,718,400 bps (bits per sec).

Figure 7.3 presents the left gray-scale image of the stereo pair, and the histogram of the image pixel values before it was manipulated.

MIX image with an blurred gray-scale image(LPF). A blurred image suffers from a lower contrast and from a loss of high spatial frequencies. Since neighboring

Figure 7.2: MIX stereo pair with No compression; a) Col - BW b) BW - Col.

pixels in a blurred image have similar values, the image contains redundant information. This resembles an image with a lower frequency content, which can be represented by a smaller amount of data, i.e. a compressed image. In our study, the original 24 bit color image was converted into an 8 bit gray-scale image by using the luminance channel after transformation to an L*a*b color space (Section 3.3.1). The gray-scale image, either left or right, was blurred with an averaging filter (3X3 kernel). The two pairs of MIX images (BWblur3 - Col, Col - BWblur3) are presented in figure Figure 7.4. Figure 7.5 presents the left blurred gray-scale image and its pixel value histogram.

image with gray-scale image after applying "Gaussian Pyramid". Image pyramid is a data structure that consists of a sequence of reduced image representations. The image pyramid contains copies of the original image in which sample density and resolution are decreased. The zero level of the pyramid consists of G_0 which is equal to the original image. G_0 is low-pass-filtered and sub-sampled by a factor of two to obtain the next pyramid level, G_1. G_1 is, in fact, a reduced version of G_0 with respect to resolution and sample density. In the same way, G_1 is filtered with the LPF weighting function and sub-sampled to obtain G_2. The remaining of the pyramid levels are obtained by repeating the LPF and subsampling steps. We refer to the pyramid of the low-pass images, i.e, the sequence of the images G_0, $G_1 \ldots G_n$, as the "Gaussian Pyramid" [6, 25]. Figure 7.8 presents the Gaussian pyramid of the left gray-scale image.

The Gaussian Pyramid technique can yield a lower bit rate for the gray-scale image. Our aim was to show that a reduced gray-scale image (in size and quality) can be transmitted, accompanied by a color image, as a MIX stereo pair, with a decoding operator on the receiver end.

This procedure was conducted over both the left and right gray-scale images that were down-sampled to create a three layered Gaussian Pyramid (G_0,G_1,G_2). The original image (1024 x 1280 pixels) is shown in Figure 7.3. The first image G_0 (left /right) was blurred using convolution with a Gaussian filter (filter kernel of dimension 5X5), then down-sampled by 2 in order to create G_1 (REDUCE operator). G_1 (512x640 pixels) was blurred and down-sampled by 2 to yield G_2 (256x320 pixels). The process is illustrated in Figure 7.8.

The image G_2 was expanded to the original image size by the *EXPAND* operator that uses the same 5X5 weighting function to generate each pyramid from its predecessors. A MIX pair was combined from one color image and one and decompressed gray-scale image. The two pairs of MIX images (BWgauss-Col, Col - BWgauss) are presented in Figure 7.9. Figure 7.7 presents the 2^{nd} level of the Gaussian Pyramid after being expanded to the original image size (8 bit, 1024 x 1280 gray scale image) and the histogram of pixel values.

The original 8 bit, 1280 x 1024 pixels, 30 frames per second yield bit rate of 314,572,800 bps. The 2^{nd} level of the Gaussian Pyramid is further reduced in size, thus yielding bit rate of 256 x 320 x 8 x 3 x 30 = 19,660,800 bps.

MIX image with 6 bit gray-scale image (Quantization). Quantization is often used in order to reduce the range of values to a single value. By reducing the number of bits in a given image, the image becomes more compressible. The original image, after being converted from the original color image into an 8 bit luminance image (as described above), was then quantized into a 6 bit image. This quantization results in a reduced range of gray-levels [0 -128] compared to the original 8 bit gray-scale image [0-256]. This does not impair image quality when perceived by a human observer, since the human eye, although able to differentiate many colors (around 350,000 colors under normal sunlight conditions), can only distinguish between 128 gray levels. The entropy, which is the lower bound on how a signal can be compressed without loss, was 5.09 for the 6 bit image while the entropy of the original 8 bit image was 7.08. The two pairs of MIX images (Col - BW6bit, BW6bit-Col) are presented in figure Figure 7.10. Figure 7.11 presents the 6 bit gray-scale image (6 bit, 1024 x 1280) and the histogram of pixel values.

A total of eight stimuli were presented in random order; each stimulus was presented twice. Table 7.1 summarizes the stimuli that were presented in the experiment. Each stimuli was presented twice. These experiments were performed on 15 subjects (10 males and 5 females) between the ages of 21 and 43. All subjects were clinically tested as discussed in Section 3.4.1. For each image pair, subjects were asked to rate their color perception on a scale of 1 to 10, with 1 denoting a gray-scale image and 10 an image in vivid colors. They were also asked to rate the depth perception from 1 to 10, with 1 corresponding to a flat image with no depth at all and 10 to a full 3D image. An HMD was used in these experiments to observe the images.

7.4 Results

7.4.1 Depth Perception of MIX Images Under Compression Conditions

Table 7.2 summarizes the descriptive statistics of depth perception for the the 3 compression methods and the original MIX pair. As can be seen from the table depth perception scores are high with very small variances thus no statistic analyses were performed on depth perception.

MIX Combination	Compression
Col-Col	No Compression
Col-BW	No Compression
BW-Col	No Compression
BW-BW	No Compression
Col -BW6bit	Quantization (6 bit)
BW6bit-Col	Quantization (6 bit)
Col -BWgauss	Gaussian Pyramid
BWgauss-Col	Gaussian Pyramid
Col - BWblur3	Average Filter (3X3)
BWblur3 - Col	Average Filter (3X3)

Table 7.1: The stimuli that were presented in the compression experiment

Stereo Type	Mean	Std.
Col-Col	9.77	0.42
Col-BW	9.67	0.52
BW-Col	9.60	0.66
BW-BW	9.70	0.65
Col-BW6bit	9.57	0.63
BW6bit-Col	9.43	0.86
Col-BWgauss	9.33	0.92
BWgauss-Col	9.20	1.13
Col-BWblur3	9.63	0.64
BWblur3-Col	9.53	0.74

Table 7.2: Descriptive statistics of depth perception (under compression)

7.4.2 Color Perception of MIX Images Under Compression Conditions

In order to test whether compression affects color perception of the MIX image an **ANOVA** analysis for repeated measures was conducted on color perception scores with **type of compression** (No compression, 6 bit presentation, Gaussian Pyramid, blur 3X3) as within- subject variables. The analysis revealed no effect of color side $F<1$, no effect of type of compression $F<1$, indicating that color perception does not depend on the three type of compression.

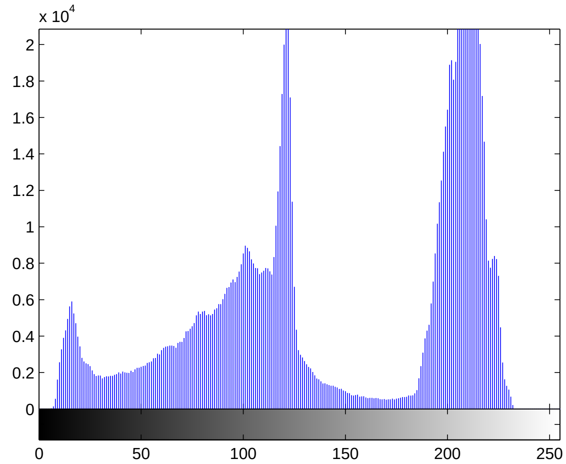
Figure 7.12 presents typical results, as measured for subject 9. Results for all subjects appear in Appendix B. Two groups, 4 bars each, are presented. The left group of the bars refers to the MIX image with the color image presented to the right eye while the right group of bars refers to the MIX pair where the color image is presented to the left eye. Each group contains 4 bars, the left most bar refers to the color perception of the MIX image in which the gray-scale image was blurred with a 3X3 kernel, the second bar from the left refers to the color perception of the MIX image in which the gray-scale image was compressed using Gaussian Pyramid, the third bar refers to the color perception of the MIX image in which the gray-scale image was converted into a 6 bit image and the rightmost bar refers to the color perception of the original MIX image (without any means of compression). The Y axis presents the color perception rating on a scale of 1 to 10.

7.5 Conclusions

The first task in designing an efficient compression algorithm is to find a representation of an image that results in a reduced storage capacity or transmission bandwidth, without losing image information or quality. Using the color redundancy in the stereo pair, by converting it into a MIX pair can serve as a first step in the compression of the stereo stream. The results presented in this chapter show that further compression can be achieved by compressing the gray-scale image by various means, without impairing image perception. All three approaches yield equivalent results concerning color and depth perception scoring. Data compression through quantization reduces the number of bits in the gray-scale image within the MIX image and preserves both color and depth perception. The same results stand when the gray-scale image is blurred. A reduced representation using Gaussian Pyramid was also proven to be an effective representation of the gray-scale image within a MIX stereo pair, that is reduced in effective data and yet does not reduce depth or color quality.

All techniques are relatively simple to implement and can be readily adapted to the reconstruction of the MIX image from the reduced resolution couple. We briefly discuss a prototype system using reduced-information monochromatic image in Chapter C. More efficient compression methods can be found in order to further compress both color and gray-scale images and yet perceive color and depth. However, the purpose of these tests was not to assess compression techniques, or quantitatively evaluate redundancies, but rather to ascertain that the basic effect can endure compression.

(a) Left gray-scale image - Original image)



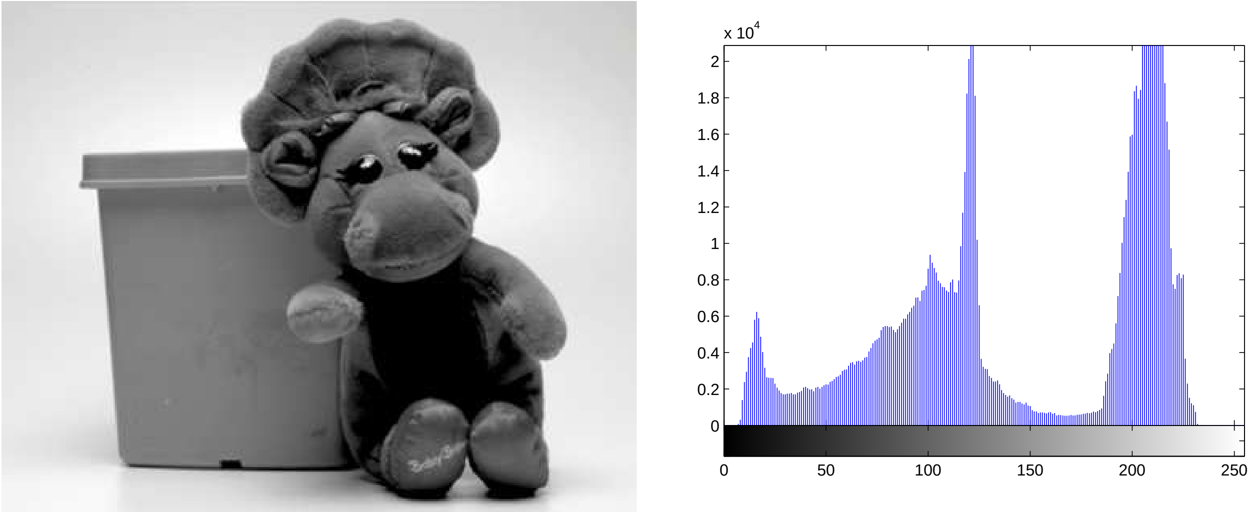
(b) Histogram

Figure 7.3: a). The original 8 bit, 1024 x 1280, gray-scale image. b) Histogram of pixel values; Entropy = 7.08 bits.

(a)

(b)

Figure 7.4: MIX pair with blurred (3X3) gray-scale image; a) Col - BWblur3, b) BWblur3 - Col



(a) left blurred gray-scale image

(b) Histogram

Figure 7.5: a). The 8 bit, 1024 x 1280, gray-scale blurred image. b) Histogram of pixel values.

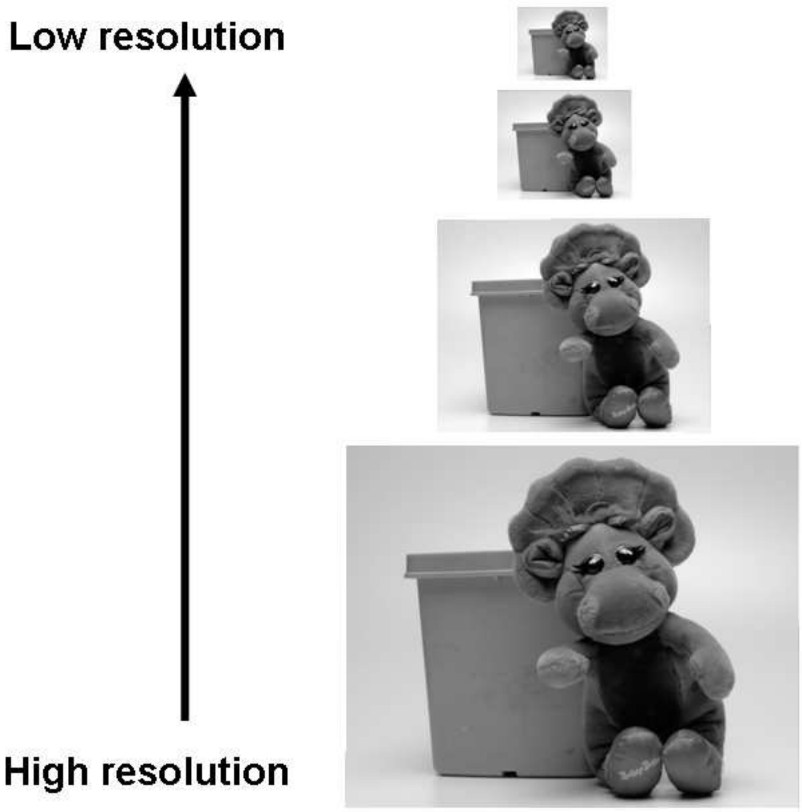
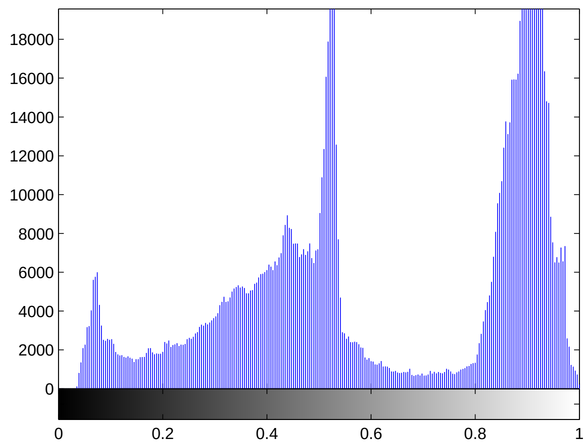


Figure 7.6: The Gaussian Pyramid of the left gray-scale image

(a) Left gray-scale image -The 2^{nd} level of the Gaussian Pyramid



(b) Histogram

Figure 7.7: a) The 2^{nd} level of the Gaussian Pyramid after being expanded to the original image size. 8 bit, 1024 x 1280, gray scale image. b) Histogram of pixel values.

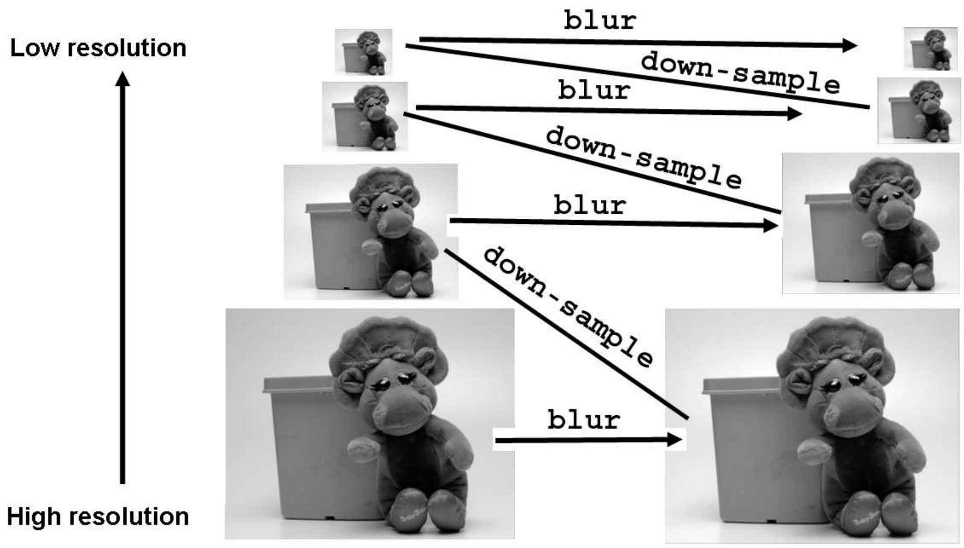
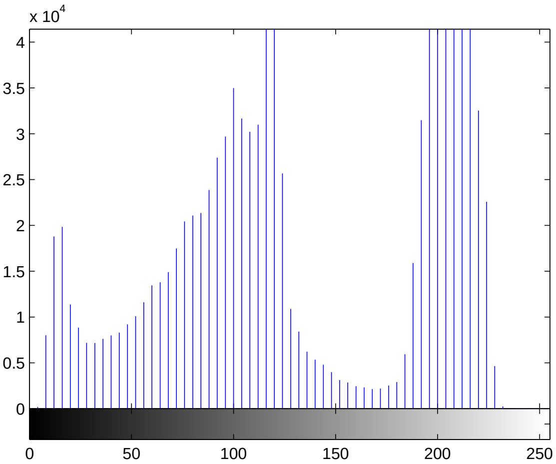


Figure 7.8: The Gaussian Pyramid process

Figure 7.9: MIX pair gray-scale image after the Gaussian Pyramid; a) Col - Bwgauss, b) BWgauss - Col

Figure 7.10: MIX pair gray-scale image after Quantization (6bit); a) Col - BW6bit b) BW6bit-Col.

(a) left gray-scale image - 6 bit



(b) Histogram

Figure 7.11: a). The 6 bit, 1024 x 1280, gray-scale image. b) Histogram of pixel values. Entropy = 5.09 bits.

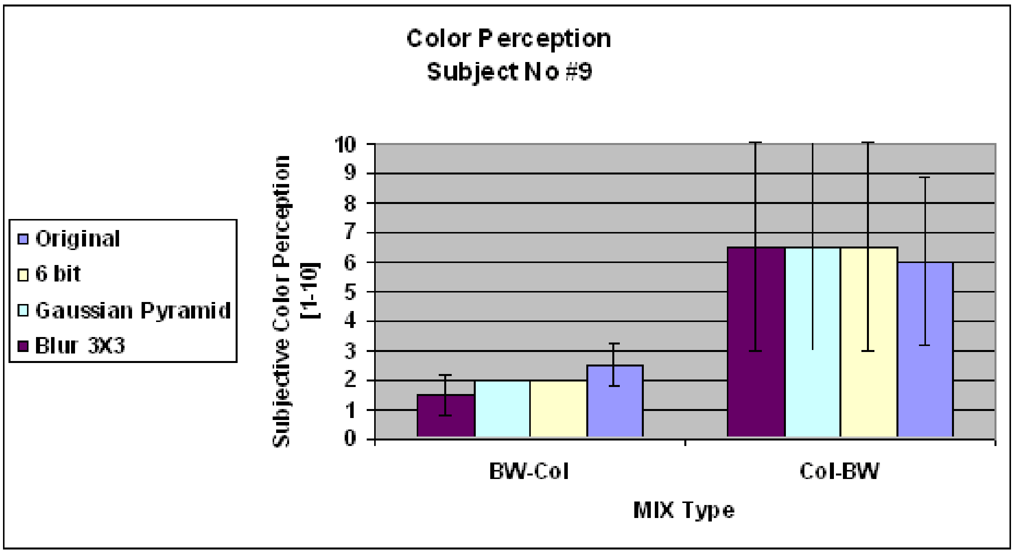


Figure 7.12: Color perception of compressed gray-scale images within the MIX images (subject No 9). Two MIX groups (BW-Col, Col-BW). The left bar: Blurred (3X3); second to the left: Gaussian pyramid; third to the left bar: 6 bit; forth to the left: No compression

Chapter 8

The Effects of Form Rivalry on Depth and Color Perception of MIX Images

Rivalry is a bi-stable perception phenomenon associated with viewing two competing stimuli. When two dissimilar images are viewed separately through the two eyes, the perceived image may alternate in an unstable manner between the two stimuli. This fluctuation in perception is the phenomenon termed *binocular rivalry* or *retinal rivalry*.

Rivalry can be triggered by a variety of stimulus differences between the left and the right eye. The stimuli can differ in color, contrast, contrast polarity, form, luminance, size or motion velocity [11].

Previous work has examined rivalry between competing colors. Treisman [94], for example, investigated color rivalry and stereopsis with green and red stimuli on a white background. She found that although the color difference clearly caused rivalry, depth perception was not affected. Even when one color image was suppressed, the information concerning contour or position was still being transferred and processed. However, no investigation has been reported concerning the perception of a monochromatic image competing with a color image.

In Chapter 4) we examined the perception of a dichoptic presentation of one color image and one gray-scale image (MIX stereo pair); a condition which our previous study [93] indicated to be fusible into a single percept. Results indicated that the lack of chromatic information in one of the stereo images does not contradict the color within the second stereo image, thus allowing for a fused 3D color percept.

In order to examine whether rivalrous conditions will influence the color and depth perception of a MIX stereo pair, and since rivalry was not the outcome of mere chromatic differences, a rivalrous pattern was added to the MIX stereo pair, in the form of a diagonal grating. The grating patches differed in orientation alone between the left and right images. The lines in the left image were rotated by 45 degrees clockwise, and the lines in the right image were rotated by 45 degrees counterclockwise.

Results show little or no effect of the existence of form rivalry on depth and color perception. Color was stable and clearly perceptible although rivalry existed, and perception of lines' direction alternated. No association was found between the direction of the lines and the color position within the stereo pair. This Chapter describes the form rivalry experiment and its results.

8.1 Related Work

Various theories try to explain the singleness of vision. This question of how the brain derives a single perceived image from two retinal images has long been debated [95, 31]. Several extensive reviews on binocular rivalry are available, including publications by Fox [28], Howard and Rogers [32, 33], Logothetis [56], Papathomas et al.,[70], Blake [11] , Alais and Blake [3] and O'Shea [69].

There are two major theories of rivalry: *Eye rivalry* [12] and *stimulus rivalry* [19, 49]. The first suggests that the eye is temporarily dominant or suppressed during rivalry. The other implies that a given "stimulus" is the one that is dominant or suppressed, i.e., rivalry occurs because of stimuli that are competing in the visual pathway [56]. There are evidences in favor of the "stimulus" based theory of rivalry, but also others that advocate the role of the "eye" in rivalry. These theories are well summarized in [11]. According to Lee and Blake [51] "stimulus rivalry" represents a different form of bi-stable perception than normal binocular rivalry, resulting from a different visual mechanism. Color rivalry was addressed in Chapter 4. This chapter introduces form rivalry into the MIX images.

8.2 Experimental Procedure

The apparatus used in this experiment was an HMD controlled by a PC. (see Section 3.2 for details). The experiment was performed on 15 subjects (10 males and 5 females) between the ages of 21 and 43. All subjects were clinically tested as described in Section 3.4.1.

A modified version of the *Bu image set* (Figure 3.10) was used in this experiment (Figure 8.1). This set will be referred to as *BuR image set*. Rivalrous patterns of diagonal lines (inclined +45 degrees on the left image and -45 degrees on the right image) were added to both images of the MIX pair. The grating was chosen to produce an orthogonal rivalrous pattern. The direction of the lines was the only parameter that was controlled.

In each set, four different combinations of image pairs were used (Col-Col, Col-BW, BW-Col, BW-BW - see Section 3.3.3 for details). A total number of eight stimuli were presented in random order; each stimulus was presented ten times. Subjects were asked to rate their depth and color perception on a scale of 1 to 10 (see Section 3.4.2). Subjects were asked to indicate whether they perceived a fused or rivalrous image in the region of the scene occupied by the grating patch. If rivalry existed, the dominant direction of lines was recorded ("Positive" for positive angle—resulting from the left eye, or "Negative" for negative angle—resulting from the right eye). Since the purpose of adding the grating patches was to test color and depth perception for the entire visual scene under forced rivalrous conditions, and not to examine the parameters of the resulting rivalry, viewing time was not limited, and no record of suppression periods in rivalry was taken.

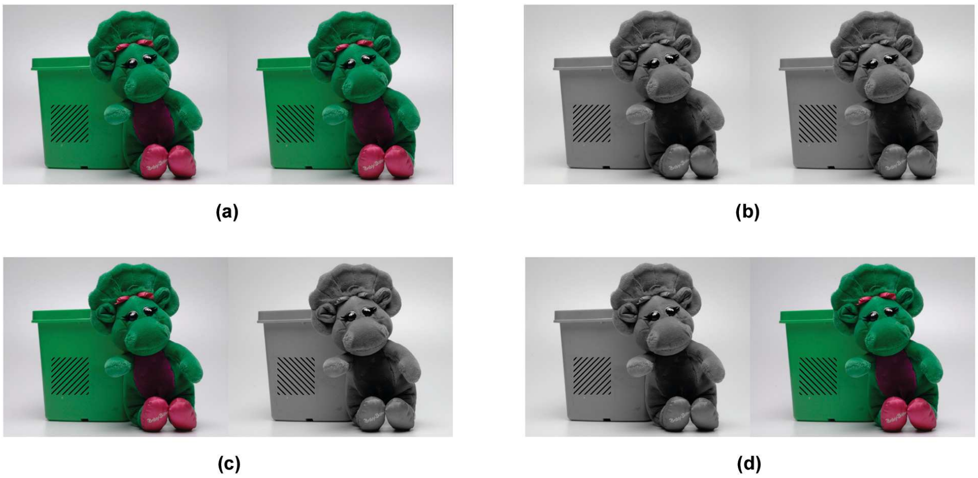


Figure 8.1: Four stereo combinations of the *Rivalry image set*. (a) (Col-Col); (b) (BW-BW); (c) MIX (Col-BW); (d) MIX (BW-Col)

8.3 Results

In general, even as the direction of the lines alternated, depth and color perception remained stable. Details are discussed below.

8.3.1 Form Rivalry Existence in MIX Images with a Grating Patch

We wanted to examine whether there is dependency between the lines' perceived direction and the color side within the stereo image. Table 8.1 summarizes the mean and Standard Deviation (Std.) of the results of the perceived direction of the lines and the results of the paired samples tests. We compared the mean responses of 'left', 'right', and 'None' direction of lines between MIX images with color on the right and MIX images with color on the left. Three *t-tests* for repeated samples were conducted on the Left, Right and 'None' responses, each comparing the two MIX images (Col-BW, BW-Col). The *t-tests* were not found to be significant, indicating that the lines' perceived direction does not depend on the color side within the stereo image.

Next, we examined the association between the perceived direction of the lines and the color side within the stereo pair separately per each subject. A *Cramér's V* test [86] was performed for each participant . The results are presented in Table 8.2. For some participants there was a null distribution of the perceived direction of the

Line perceived Direction	Stereo Type	Mean	Std.	t	p (2-tailed)
Left	Col-BW	1.93	3.22	-1.317	0.209
	BW- Col	2.53	3.94		
Right	Col-BW	2.80	3.53	1.703	0.111
	BW- Col	2.07	3.03		
None	Col-BW	5.27	4.18	-0.70	0.499
	BW- Col	5.40	4.39		

Table 8.1: Means and Std. of Left,Right and 'None' direction of lines by MIX images (form rivalry)

lines, therefore *Cramér's V* test was not computed for these participants (marked as '-'). The results indicate that only for two participants (subject No and subject 12) there was an association between the perceived direction of the lines and the color side.

Subject No	P	Cramér's V)
Subject No 1	0.56	0.24
Subject No 2	-	-
Subject No 3	-	-
Subject No 4	-	-
Subject No 5	0.1	0.39
Subject No 6	0.58	0.22
Subject No 7	-	-
Subject No 8	0	1
Subject No 9	0.62	0.33
Subject No 10	0.51	0.36
Subject No 11	0.38	0.28
Subject No 12	0.00089	0.75
Subject No 13	-	-
Subject No 14	0.49	0.25
Subject No 15	0.44	0.38

Table 8.2: The association between the perceived direction of the lines and the color side

Next we examined Next, we examined whether there is an association between perceived lines dierection and dominant eye. First, we computed for each subject the mean number of "left", "right" and "None" answers across the four image combinations. Next, three *t-tests* for independent samples were conducted on these means each with dominant eye (left/right) as independent variable. Table 8.3 presents means and Std. of "left", "right", and "None" answers by dominant eye and the outcomes for the T-Tests. Results indicated that the mean answer of "right" direction (that was presented dichoptically to the left eye) was higher for participants with a left dominant eye than with a right dominant eye. An opposite tendency emerged for the left answer although it did not reach statistical significance. It should be noted that the power of this test is quit low due to the small No of participant for each group of dominant eye. Nevertheless these tendencies have opposite direction for the right and left eye as was expected.

Line Dominant Direction	dominant Eye	N	Mean	Std.	p (2-tailed)
Left	Left	7	0.36	0.84	0.092
	Right	8	3.00	3.74	
Right	Left	7	4.14	4.05	0.042
	Right	8	0.75	1.29	
None	Left	7	5.5	4.41	0.73
	Right	8	6.25	3.93	

Table 8.3: Group statistics (form rivalry)

8.3.2 Depth Perception of MIX Images Under Form Rivalry Conditions

Depth was perceived in all four combinations of stereo images bounded with form rivalry that were presented to the subjects. Table 8.4 summarizes the mean and Standard Deviation (Std.) of the depth perception score per each stimulus. The stimuli are categorized according to "Stereo Type" (Col-Col/Bw-Bw/BW-Col,Col-BW) and "Rivalry" (Yes/No). These results are also graphically presented in Figure 8.2. As can be seen, all subjects in all viewings rated depth as a maximum (10).

Stereo Type	Rivalry	Mean	Std.
Col-Col	No	10	0.0
Col-Col	Yes	10	0.0
BW-BW	No	10	0.0
BW-BW	Yes	10	0.0
Col-BW	No	10	0.0
Col-BW	Yes	10	0.0
BW-Col	No	10	0.0
BW-Col	Yes	10	0.0

Table 8.4: Descriptive statistics of depth perception (under form rivary)

8.3.3 Color Perception of MIX Images Under Form Rivalry Conditions

We wanted to further investigate whether form rivalry has any effect on color perception of the MIX stereo pair. Figure 8.3 presents the color perception scores for each of the four stereo combination with and without rivalry. The X-axis separates the stereo combinations (Col-Col, Col-BW, BW-Col, BW-BW). The Y-axis denotes

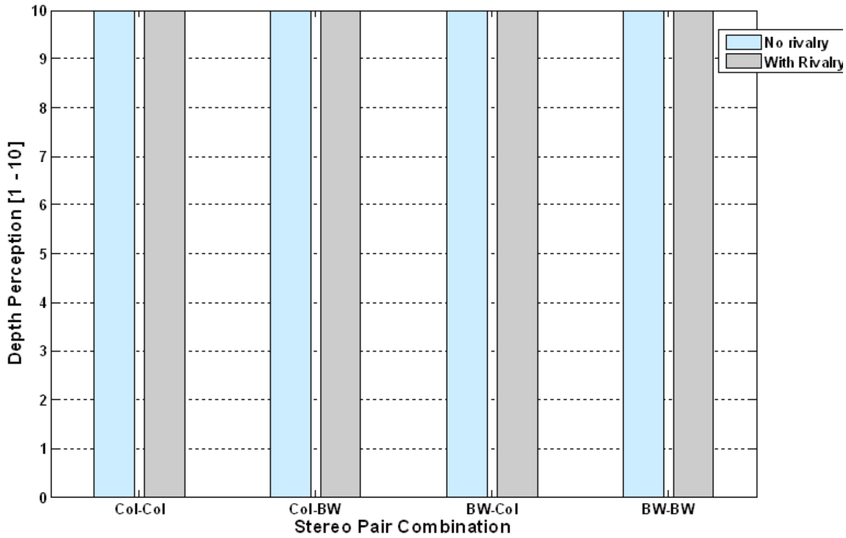


Figure 8.2: Depth perception of four Stereo combinations with and without rivalry

the color perception score on a scale of 1-10 described earlier. For each stereo combination two bars are presented: The left bar presents the color perception score with no form rivalry and the right bar presents the color perception of the stereo pair with the rivalrous pattern. Analysis revealed that the form rivalry had practically no effect on color perception, as color scores for both patterns were less than 1 Std.

Stereo Type	**Rivalry**	**Mean**	**Std.**
Col-Col	No	9.9333	0.15887
Col-Col	Yes	9.9600	0.12984
Col-BW	No	5.9133	1.90408
Col-BW	Yes	6.8067	1.86144
BW-Col	No	6.7200	1.67084
BW-Col	Yes	6.7933	1.63378

Table 8.5: Descriptive statistics of color perception (rivary)

8.4 Conclusions

When the images from both eyes differ in a way that the brain cannot reconcile, binocular rivalry or suppression takes place. When rivalry occurs, one eye's image dominates perception while the other eye is suppressed. MIX stereo pairs were found to cause no color rivalry. Form rivalry, when forced onto the four stereo combinations, yielded 3D color images with rivalry and suppression that occurred only within the line patterns.

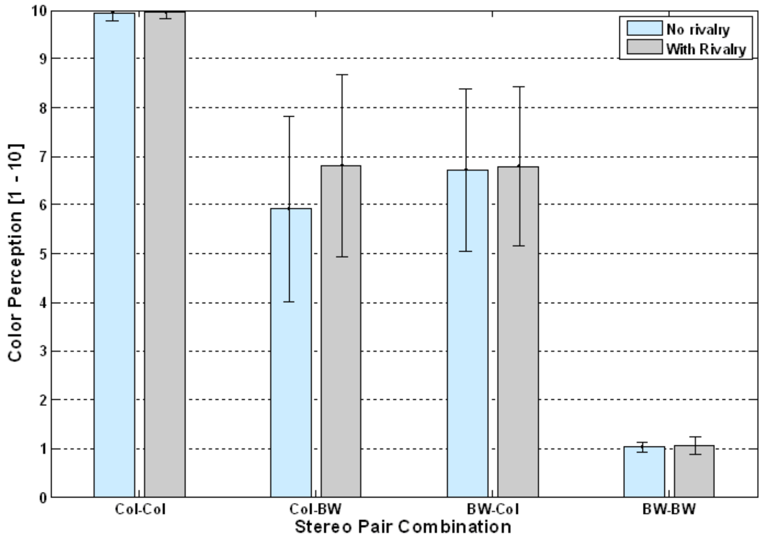


Figure 8.3: Color perception of four stereo combinations with and without rivalry.

Rivalry or suppression of incompatible direction of lines, although present, had little effect, if any, on the perception of color.

However, reports of subjects after viewing the images with grating patches raised the issue that there is room for further examination of the extent to which these patches actually influence rivalry vs. fusion for the entire image.

Blake has found that the region of suppression may be spatially limited to the vicinity of the grating pattern. Since the stimuli in the MIX color and depth scoring are large, and occupy a large portion of the retina, different regions of the eye can be in different states of rivalry [10, 11]. Target areas may have been in fusion state while patch areas were not. Further tests can be performed with patterns that are presented in different regions of the eye.

Chapter 9

Future Work

The investigations described in this dissertation are only first steps towards exploring the interesting phenomenon of the perception of color stereoscopic images by the human brain. Numerous questions are raised by the research, and will require further research.

The experiments' results show that some degradation in color exists when viewing MIX stereo pairs, as compared to the full-color pairs. We feel that a natural continuation of this research is the quantification of the shift in perceived color within the color space. This can shed more light on the color mechanisms that contribute to the binocular color perception of the MIX images. Moreover, understanding this shift may potentially lead to correcting it automatically on the receiving end, leading to a stereoscopic image that is comparable to the full-color image.

We conducted preliminary experiments in order to quantify this shift and assess which axis in the HSV (Hue, Saturation, Value) color space is more influenced by it. The preliminary results suggest that the hue component of the target's perceived color is least affected when viewing a MIX image. Value components are most affected, in a manner that can be modelled by an approximated average between the observed intensities of both images in the MIX pair. The results with respect to the S component are inconclusive. However, the results are promising. If indeed color shifts are quantified, and found to be most affected in their luminance values, image perception may be improved by manipulating the appropriate color-space axes when creating the MIX image pairs.

Other psychophysical questions are raised by our work. Research of the psychophysical properties of these phenomena might greatly benefit from fMRI experiments. These experiments can demonstrate the cortical activity during MIX viewings, thus mapping the cortical areas and mechanisms, and possibly settling suppression vs. fusion debates.

Exploring the asymmetric color perception of the MIX images, and its association with the position of the color image within the MIX pair, can lead to interesting research directions on the subjects of brain asymmetry, eye dominance, and oculomotor functionality.

There are many potential directions for future work on the practical side of this research. For instance, the fusion of MIX images can also be investigated during platform or scene movement, and under varying lighting and contrast conditions.

We have carried out some preliminary experiments in implementing the stereo MIX video-feed, as a basis for the remote operation of a mobile robot. Figure 9.1 presents the stereo robotic system (named: ESTHER) that was built on a Friendly Robotics' vacuum cleaner (RV 400) platform. It is comprised of two SONY color video cameras (EVI-401DR) and two video transmitters (Figure 9.2). The output of one of the cameras was of course degenerated into a luminance-only channel source, i.e., a monochromatic image. Early results demonstrate that users perceive color and depth, although with some degradation in color perception, and are able to carry out their tasks successfully.

Figure 9.1: ESTHER: The stereo robotic system

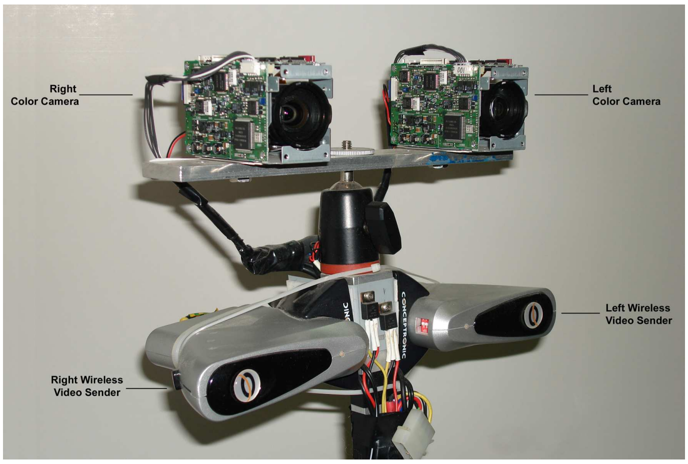


Figure 9.2: ESTHER: The stereo cameras and transmitters

Chapter 10

Conclusions and Discussion

Several psychophysical experiments were conducted on human subject with normal vision in order to demonstrate that when two stimuli that differ in chromatic content were viewed dichoptically, the images from both eyes fused into a single coherent percept. Five image sets were used, and two apparatus: A stereoscope and an HMD.

The results show that as a rule, subjects successfully fused the MIX images in all image sets. Subjects perceived a 3D image in terms of depth, irrespective of the color differences in a given image pair. Color perception was achieved in all MIX cases, even though some degradation of color quality can be seen in the results.

It is known that different stimuli presented dichoptically to each eye usually cause rivalry. This rivalry implies that the visual system cannot perceive a stable perception of the stimuli obtained from the two eyes and it either rejects one of the images or alternates between them in unstable state. Since the visual system can avoid rivalry by suppressing one of the dissimilar images that are presented to the two eyes, and since the system seeks strong perceptive coherence, we believe that the channel that carries the color information has more weight than the channel that carries the monochromatic information, which is likely to be partially or totally suppressed.

These results clearly show that the interaction of the MIX stimuli between the two eyes is possible and confirm that the color mechanism involved in this process must be beyond the monocular mechanism in the cortex. Moreover, since a 3D image is obtained regardless of color content, the color generation is binocularly driven and it takes place later in the cortex. The color reproduced in the interocular interaction is not limited to a specific color content of the image although better results were obtained with unsaturated color content (the *yellow image set*). Our results are consistent with the findings of Land [50, 64], that the color generating mechanisms are combined of two stages, located at different sites of the human brain: The first stage does not include any binocular neurons and merely compares color (wavelength) information across space, whereas the second is binocular in nature, since it occurs after the convergence of the input from the two eyes and combines the results of the first stage.

Figure 4.7 modified from [34], portrays the information flow of the scheme that was presented to subjects (a MIX stereo pair viewed dichoptically) within the visual pathway. The images obtained from the right and left visual field are collected by the left and right retinal halves of both eyes, respectively. Each hemisphere therefore gets input from both eyes. After decussation (crossover) at the optic chiasm, color information is available to both hemispheres and the fact that the retinal image is inverted was neglected.

Several questions were raised by these results. First, all subjects showed a clear preference to a specific eye when viewing a MIX color stereo pair. Color perception scores were significantly higher when the color image was presented to their preferred eye. The connection between this preferred eye and the subject's dominant eye, as defined in optometric terms, was further investigated.

The two variations of MIX combinations (Col-BW and BW-Col) yielded different color scores in a majority of the subjects and trial types, with one eye appearing to be dominant for color. When all three stimuli types scores are combined, 11 of the 15 subjects showed a significant preference for one eye over the other. That is, the color was significantly more vivid when shown to that eye than when shown to the other eye. These results show an asymmetry in color perception. In other words, color perception, which theoretically should be side-indifferent, still has a preferred side.

In addition, positive association was found between: (i) the preferred color side and the dominant sighting eye; and (ii) the preferred color side and the dominant hand. However, these findings should be taken with caution because of the relatively small sample. Future research should further investigate if this is an evidence for a new eye dominance criteria.

The most straightforward means for influencing the predominance of the color image over the gray-scale image is to vary some aspects of the competing stimuli. These manipulations are described in the literature with variables as contrast, luminance, contour density, frequency, size etc. [11]. Images that differ in their color content (MIX image) and sharpness (blur) were presented to subjects in order to check whether fusion, rivalry or suppression occurs. Blur was introduced to one or both of the images in the MIX stereo pair. The blurring effect was achieved by applying an averaging filter with a kernel of 3X3 or 5X5 pixels to the image.

Several questions were investigated: (1) Are there any differences in depth and color perception when blurring one or both of the images in the MIX stereo pair? (2) Is there a difference in depth and color perception when blur is applied to the gray-scale image versus the color image? (3) Is color perception affected by the blurring level (3X3 or 5X5 kernel) of the image, and by which image that was blurred (color or gray-scale)?

The results reveal that color perception of MIX stereo pair can be further improved when the gray-scale image is blurred, while depth perception remains intact. Moreover, this implies that the amount of data in the gray-scale image can further be reduced. These finding is the basis for further investigation on the subject of compression.

The first task in designing an efficient compression algorithm is to find a representation of an image that results in a reduced storage capacity or transmission bandwidth, without losing image information or quality. Using the color redundancy in the stereo pair, by converting it into a MIX pair can serve as a first step in the compression of the stereo stream.

We therefore examine the effect of applying three different compression methods to gray-scale image within a stereo pair, to achieve such further data reduction. Results show that further compression can be achieved by compressing the gray-scale image by various means, without impairing image perception. All three approaches yield equivalent results concerning color and depth perception scoring.

In particular, data compression through quantization reduces the number of bits in the gray-scale image within the MIX image and preserves both color and depth perception. The same results stand when the gray-scale image is blurred. A reduced representation using Gaussian Pyramid was also proven to be an effective representation of the gray-scale image within a MIX stereo pair, that is reduced in effective data and yet does not reduce depth or color quality. All techniques are relatively simple to implement and can be readily adapted to the reconstruction of the MIX image from the reduced resolution couple. A first implementation using MATLAB and SIMULINK on a simple system with two web cameras is presented in appendix C. While more efficient ways can be found to further compress both the images, the purpose of these tests was not to assess compression techniques, or quantitatively evaluate redundancies, but rather to ascertain that the basic effect can endure compression. The results support this hypothesis.

When the images from both eyes differ in a way that the brain cannot reconcile, binocular rivalry or suppression takes place. When rivalry occurs, one eye's image dominates perception while the other eye is suppressed. It is well known that rivalry can be triggered by a variety of stimulus differences between the left and the right eye. The stimuli can differ in color, contrast, contrast polarity, form, luminance, size or motion velocity [11]. Previous work has examined rivalry between competing colors. Treisman [94], but no investigation has been reported concerning the perception of a monochromatic image competing with a color image.

Our research (of which a first part was published; see [93]) indicates that MIX stereo pair is fusible into a single percept, and causes no color rivalry. In other words, the lack of chromatic information in one of the stereo images does not contradict the color within the second stereo image, thus allowing for a fused 3D color percept. Form rivalry, that was forced onto the four stereo combinations, yielded 3D color images with rivalry and suppression that occurred only within the line patterns. Rivalry or suppression of incompatible direction of lines, although present, had little effect, if any, on the perception of color. However, reports of subjects after viewing the images with grating patches raised the issue that there is room for further examination of the extent to which these patches actually influence rivalry vs. fusion for the entire image.

To conclude, the proposed approach for reducing bandwidth by using only one color camera appears to be a viable complementary approach to current techniques used in transmitting color 3D images. In addition, reducing the resolution of one of the images does not significantly detract from the reported effect. There are several potential shortcomings to using this approach. The most obvious, based on the presented data, is that although the hypothesis that a MIX pair will be seen in color has been validated, it is clear that the color in that scenario is less vivid than in a color pair. Investigation of the color degradation, variance between subjects and means for improving the color perception score will be explored in future work.

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Appendix A

Free-View

It may be possible for the reader to experience this phenomenon using a limited free-viewing example (without the use of glasses) (Figure A.1). A stereoscopic image pair from [59] was replicated, and one of the images was converted to gray-scale. When printed in color, the images can be fused into a stereoscopic image, by simply free viewing them from a short distance from the sheet. There are two ways to free view the images in stereo: parallel or crossed-eyed. In parallel viewing, the eyes are to be focused before the image while orienting them to look at infinity. The right eye sees the right image and the left eye sees the left image. Cross-eyed viewing involves crossing your eyes so that your right eye sees the left image and vice versa. We provide examples of both. Figure A.1-a shows a left-right stereo pair, parallel axes, which can be viewed with the eyes converged (cross-eyed). Figure A.1-b is similar, but is intended to be viewed with the eyes parallel. Viewers typically prefer one or the other. Some readers may find it hard to fuse images without the use of optical aids.

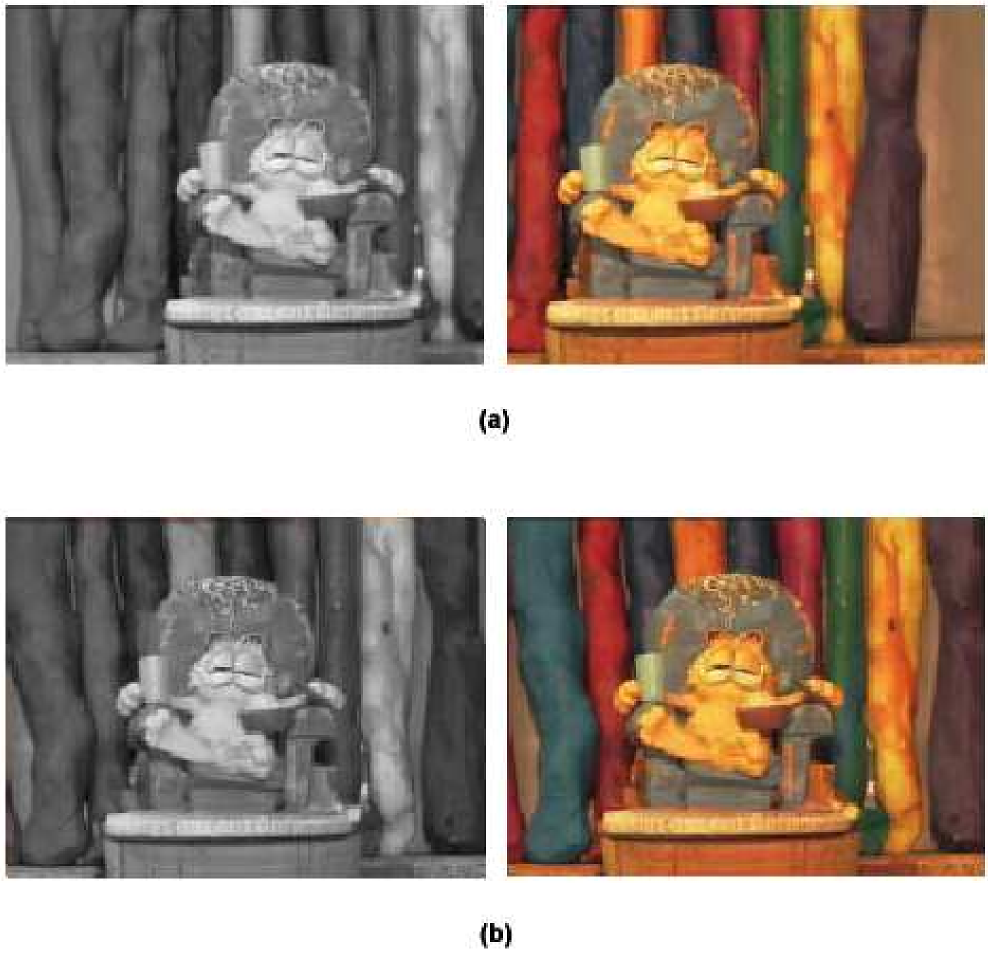

Figure A.1: "Free-viewing" of MIX color stereo pairs. (a) is viewed with the eyes converged. Cross your eyes so that each eye views the opposite image (left eye sees right image and vice versa). (b) is viewed with the eyes parallel (left eye sees left image and vice versa).

Appendix B

Compression

This appendix presents the color perception scores of the compressed MIX images as were obtained for each subject separately. The gray-scale image was compressed in three different techniques as described in (Chapter 7.

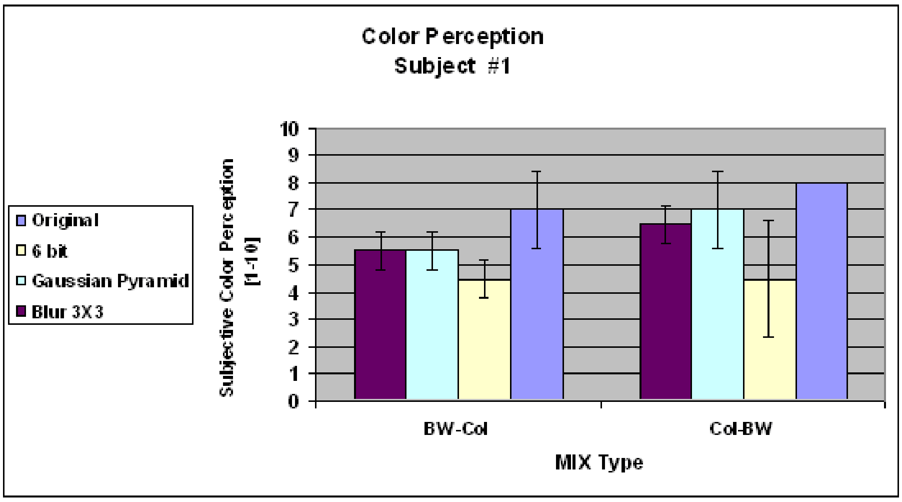

Figure B.1: Color perception of compressed gray-scale images within the MIX image pair (subject No 1). Two MIX groups are presented(BW-Col, Col-BW), 4 bars each . The left bar: Blurred (3X3); second to the left: Gaussian pyramid; Third to the left bar: 6 bit; forth to the left: No compression

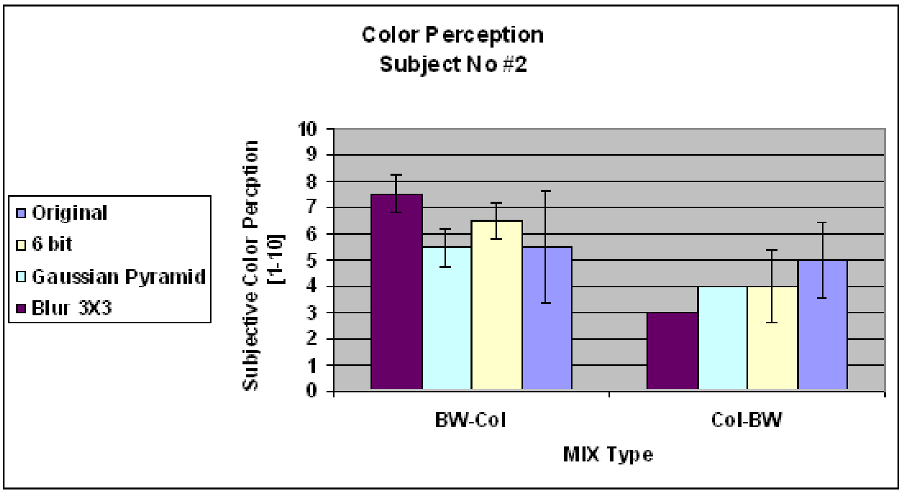

Figure B.2: Color perception of compressed gray-scale images within the MIX images (subject No 2). Two MIX groups are presented(BW-Col, Col-BW), 4 bars each . The left bar: Blurred (3X3); second to the left: Gaussian pyramid; Third to the left bar: 6 bit; forth to the left: No compression

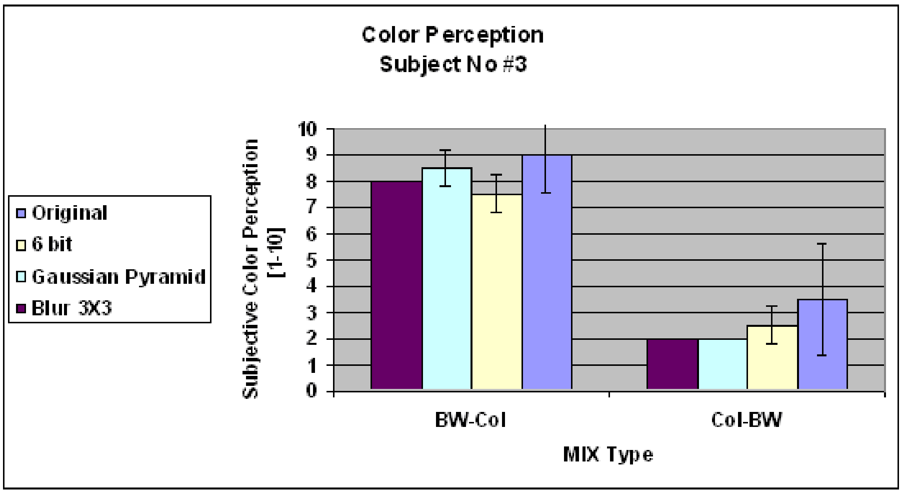

Figure B.3: Color perception of compressed gray-scale images within the MIX images (subject No 3). Two MIX groups are presented(BW-Col, Col-BW), 4 bars each . The left bar: Blurred (3X3); second to the left: Gaussian pyramid; Third to the left bar: 6 bit; forth to the left: No compression

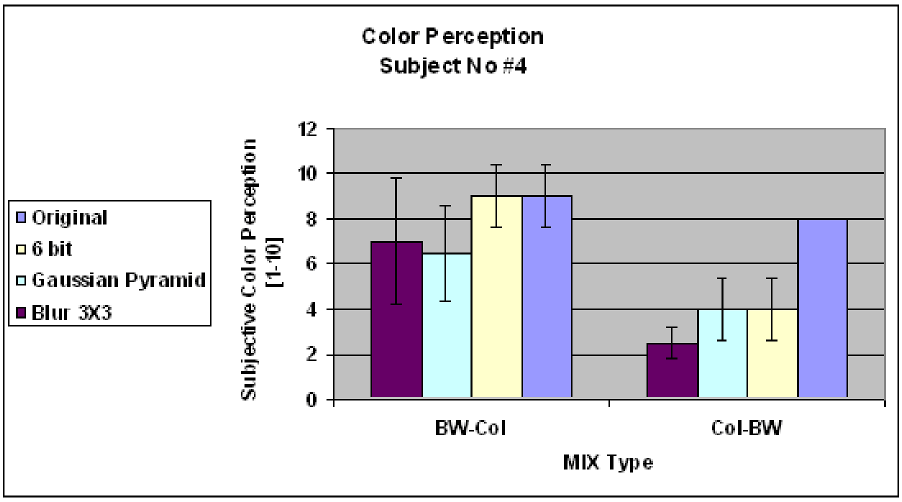

Figure B.4: Color perception of compressed gray-scale images within the MIX images (subject No 4). Two MIX groups are presented(BW-Col, Col-BW), 4 bars each . The left bar: Blurred (3X3); second to the left: Gaussian pyramid; Third to the left bar: 6 bit; forth to the left: No compression

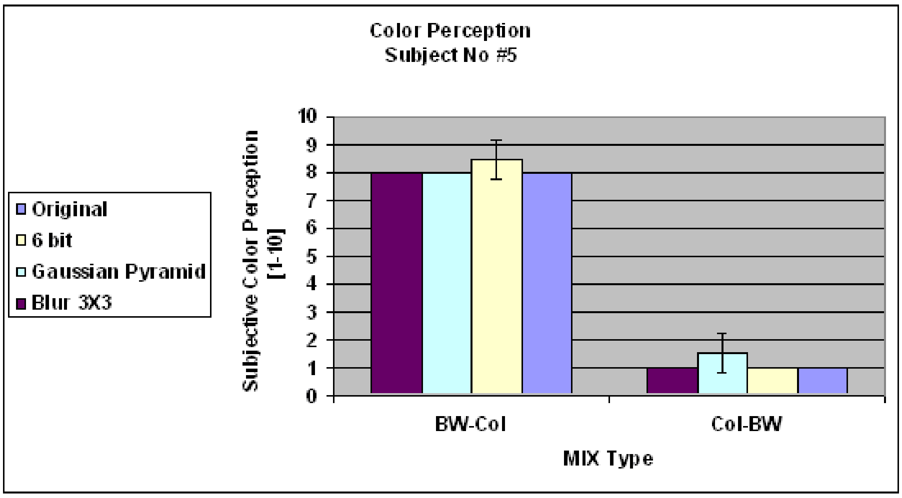

Figure B.5: Color Perception of compressed gray-scale images within the MIX images (subject No 5). Two MIX groups are presented(BW-Col, Col-BW), 4 bars each . The left bar: Blurred (3X3); second to the left: Gaussian pyramid; Third to the left bar: 6 bit; forth to the left: No compression

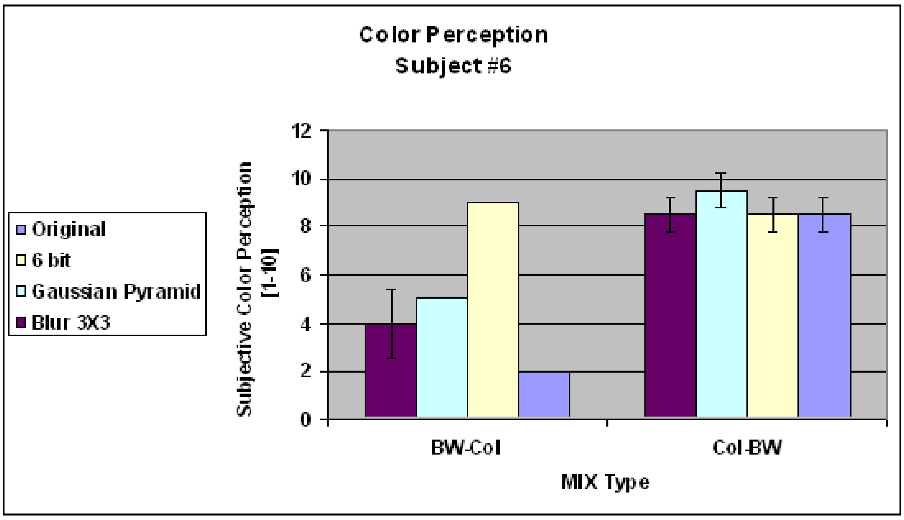

Figure B.6: Color perception of compressed gray-scale images within the MIX images (subject No 6). Two MIX groups are presented(BW-Col, Col-BW), 4 bars each . The left bar: Blurred (3X3); second to the left: Gaussian pyramid; Third to the left bar: 6 bit; forth to the left: No compression

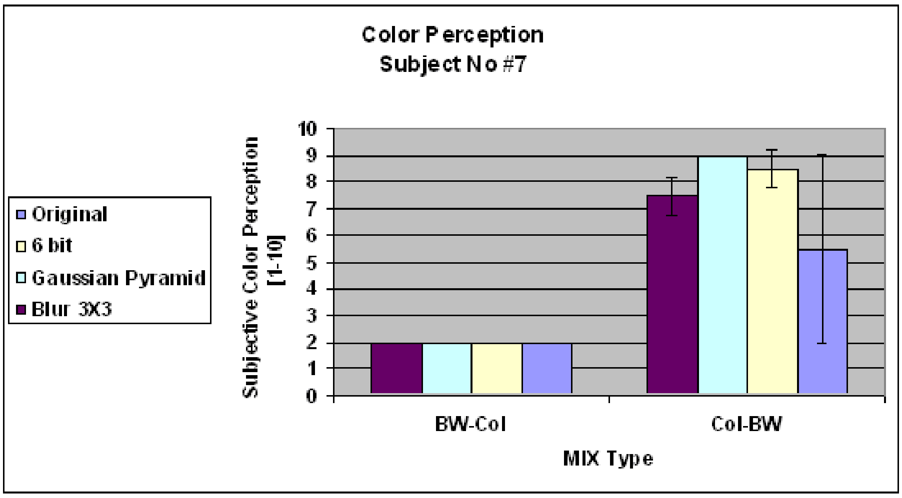

Figure B.7: Color perception of compressed gray-scale images within the MIX images (subject No 7). Two MIX groups are presented(BW-Col, Col-BW), 4 bars each . The left bar: Blurred (3X3); second to the left: Gaussian pyramid; Third to the left bar: 6 bit; forth to the left: No compression

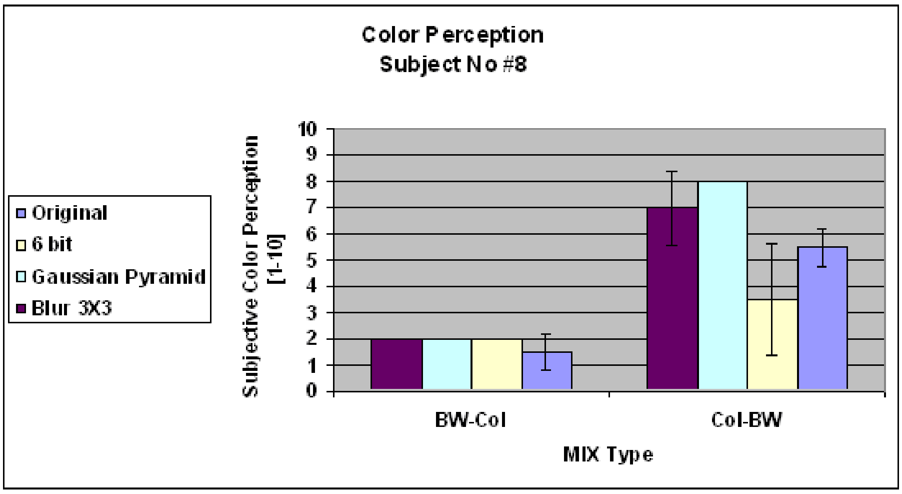

Figure B.8: Color perception of compressed gray-scale images within the MIX images (subject No 8). Two MIX groups are presented(BW-Col, Col-BW), 4 bars each . The left bar: Blurred (3X3); second to the left: Gaussian pyramid; Third to the left bar: 6 bit; forth to the left: No compression

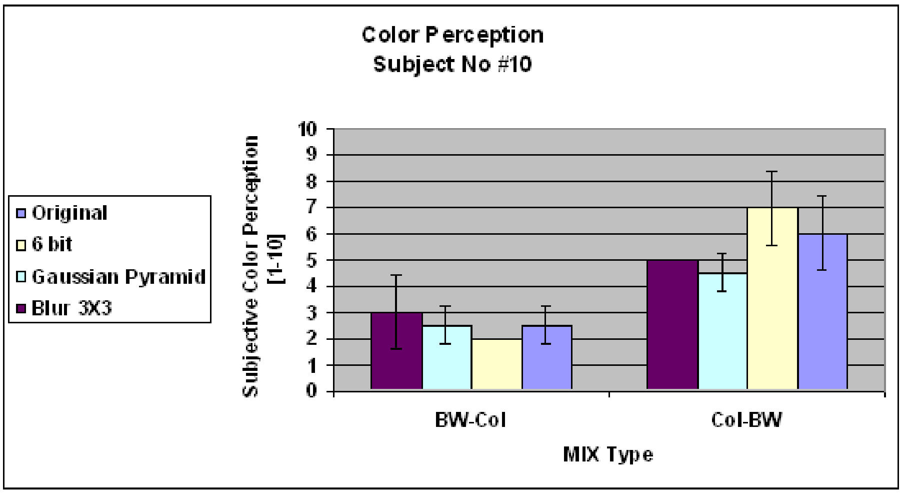

Figure B.9: Color perception of compressed gray-scale images within the MIX images (subject No 10). Two MIX groups are presented(BW-Col, Col-BW), 4 bars each . The left bar: Blurred (3X3); second to the left: Gaussian pyramid; Third to the left bar: 6 bit; forth to the left: No compression

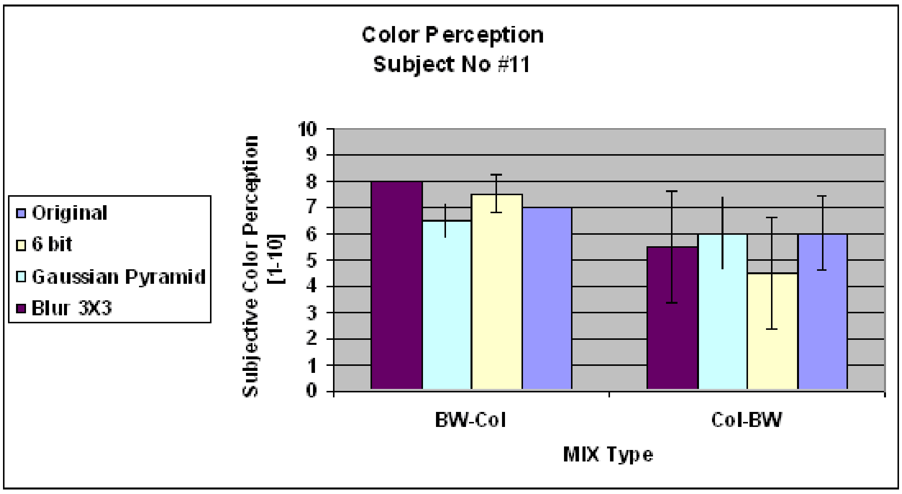

Figure B.10: Color perception of compressed gray-scale images within the MIX images (subject No 11). Two MIX groups are presented(BW-Col, Col-BW), 4 bars each . The left bar: Blurred (3X3); second to the left: Gaussian pyramid; Third to the left bar: 6 bit; forth to the left: No compression

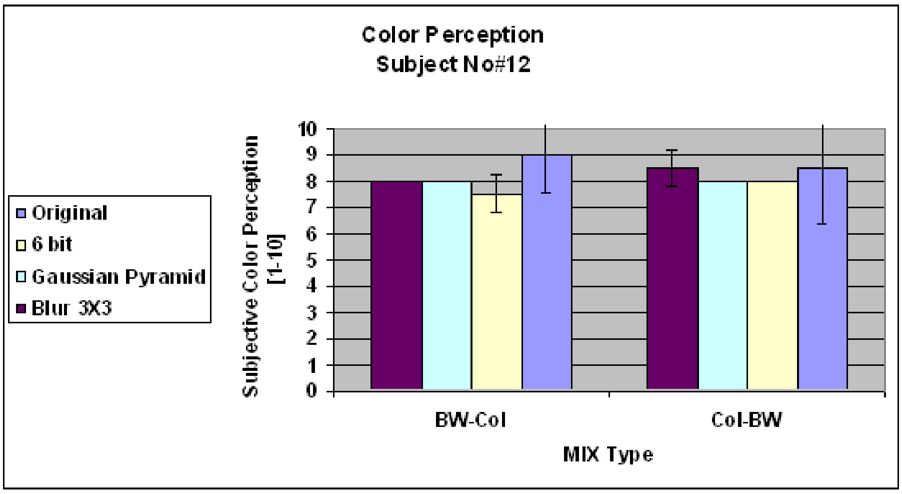

Figure B.11: Color perception of compressed gray-scale images within the MIX images (subject No 12). Two MIX groups are presented(BW-Col, Col-BW), 4 bars each . The left bar: Blurred (3X3); second to the left: Gaussian pyramid; Third to the left bar: 6 bit; forth to the left: No compression

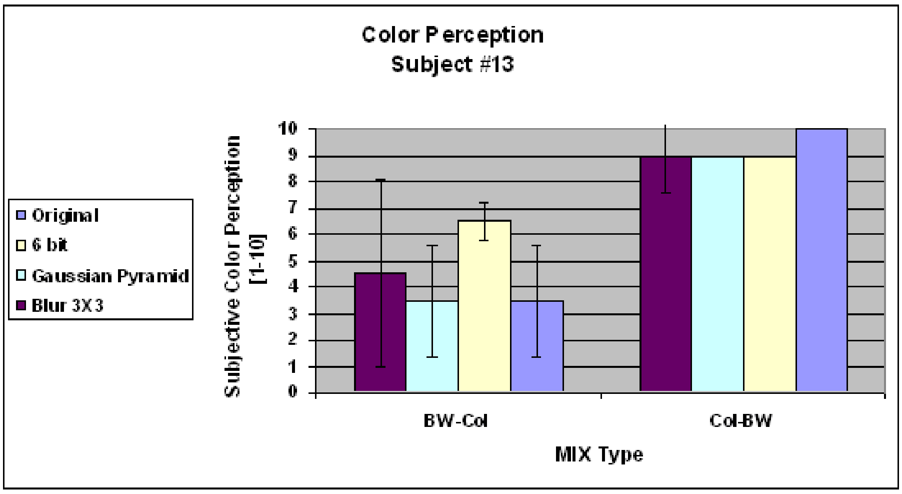

Figure B.12: Color perception of compressed gray-scale images within the MIX images (subject No 13). Two MIX groups are presented(BW-Col, Col-BW), 4 bars each . The left bar: Blurred (3X3); second to the left: Gaussian pyramid; Third to the left bar: 6 bit; forth to the left: No compression

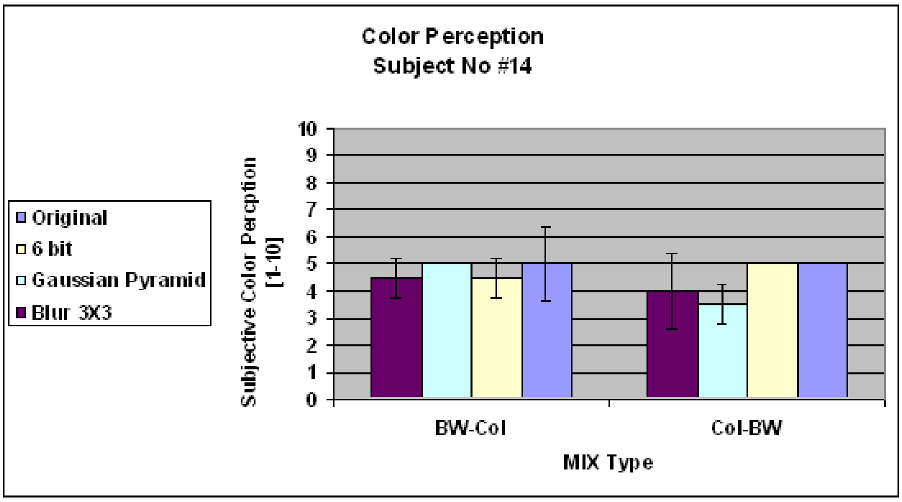

Figure B.13: Color perception of compressed gray-scale images within the MIX images (subject No 14). Two MIX groups are presented(BW-Col, Col-BW), 4 bars each . The left bar: Blurred (3X3); second to the left: Gaussian pyramid; Third to the left bar: 6 bit; forth to the left: No compression

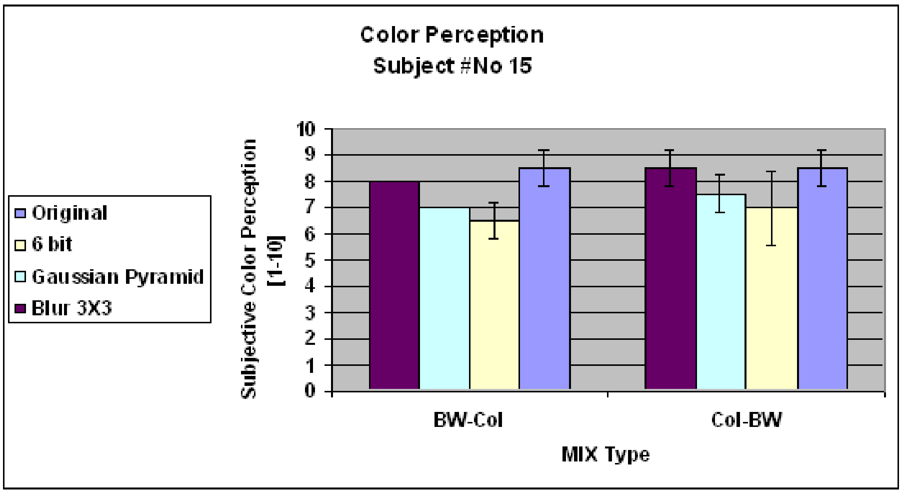

Figure B.14: Color perception of compressed gray-scale images within the MIX images (subject No 15). Two MIX groups are presented(BW-Col, Col-BW), 4 bars each . The left bar: Blurred (3X3); second to the left: Gaussian pyramid; Third to the left bar: 6 bit; forth to the left: No compression

Appendix C

Real Time Simulation using Simulink

The simulator was built using the SIMULINK environment (a platform for multi-domain simulation and Model-Based Design), that simulated a dynamic real-time MIX stereo stream scenario. The block diagram presented in Figure C.1 presents the general scheme.

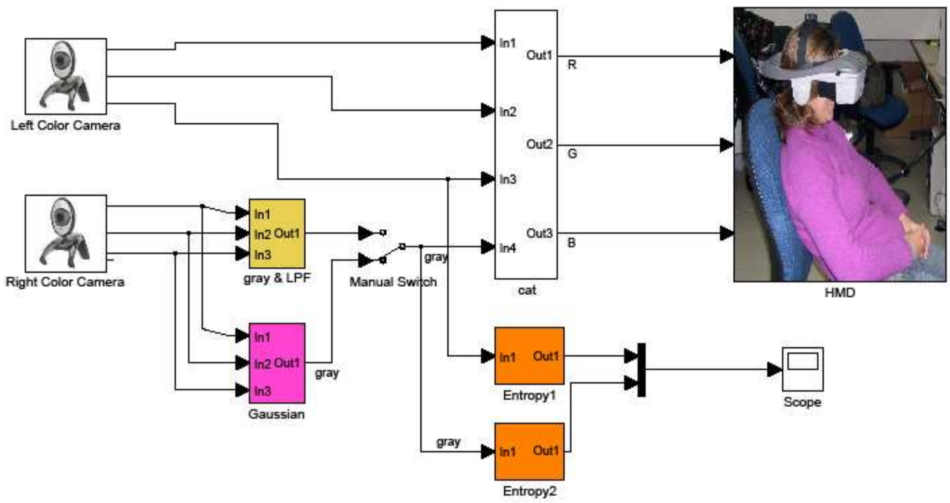

Figure C.1: The general SIMULINK scheme

The hierarchical module contains four major components:

1. Two camera sources.

2. Gaussian Pyramid construction.

3. Low Pass Filter.
4. Entropy calculation.
5. Two image concatenation.

Two camera sources. The Camera inputs can be configured by the camera configuration file for different parameters settings, e.g. frame rate, image type and size. The camera itself could be an internet USB camera or such with a frame grabber card.

Gaussian Pyramid construction / Low Pass Filter. First, an RGB image is converted into a double precision gray-scale image and a Gaussian Pyramid is built using the **Reduce** procedure for some input level parameters. (See Section 7.3 for details). The image at the top of the pyramid is then used for reconstruction using the **Expand** procedure. At this stage the obtained image is the input image after 'reducing' n times and 'expanding' back n times. Another option which is implemented in the module is filtering the image with a LPF instead of down and up scaling the image with a Gaussian Pyramid. The choice between the Gaussian Pyramid and LPF is up to the user to decide. Figures C.2, C.3 present the details of each of the blocks. Similarly, any other compression method can easily be implemented as an independent block and inserted into the main model.

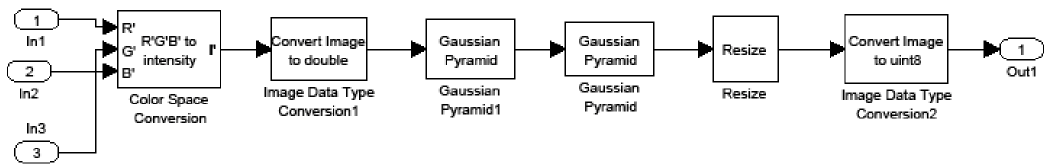

Figure C.2: The Gaussian Pyramid Block

Entropy calculation .

Some basic blocks of SIMULINK were used in order for constructing the entropy formula as is detailed in the scheme in Figure C.4. The entropy of both frames ,color input and the gray-scale, are calculated and presented on a "scope" for mean of observation.

Figure C.5 shows a snapshot from the two video streams. Note that the monochromatic video stream on the right is also blurred

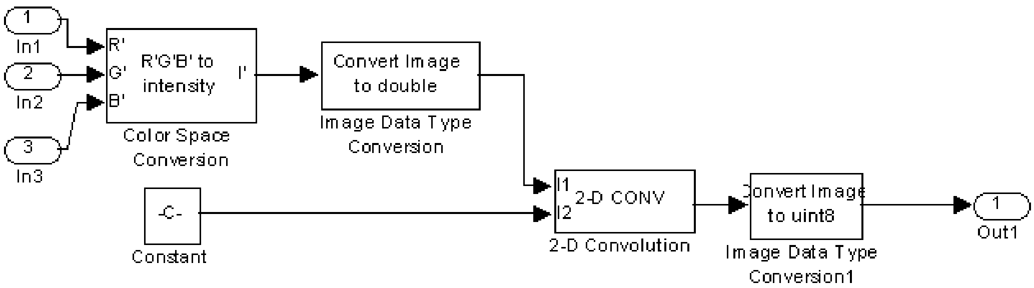

Figure C.3: The LPF Block

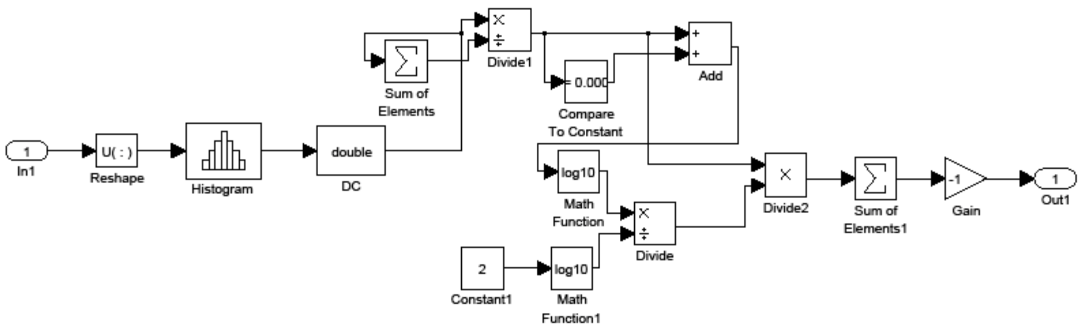

Figure C.4: The Entropy Block

Figure C.5: The MIX stereo video frame

תקציר

ראייה סטריאוסקופית היא אחת ממשימות הראיה המעניינות והשימושיות ביותר בחיי היום-יום שלנו.

הראייה הסטריאוסקופית מאפשרת תפיסה של מימד העומק, מקלה על היכולת שלנו לנווט בקלות ובבטחה בעולם התלת- מימדי המקיף אותנו וכן מאפשרת התמצאות, גילוי, זיהוי והכרה של עצמים בשדה הראיה. ראיית הצבע מספקת לנו אינפורמציה נוספת שחשובה אף היא ליכולת שלנו לתפקד בעולם ומקלה בתהליך הזיהוי וההפרדה של אובייקטים מהרקע.

התפיסה הויזואלית המתקבלת ממערכת הראיה האנושית היא תוצאה של תהליך חישובי מורכב. היא אינה תוצאה של חיבור פשוט של המידע משתי התמונות המתקבלות משתי העיניים.

עובדה ידועה היא, שניתן לחוות עומק מצפייה דרך סטריאוסקופ בתמונת סטריאו המורכבת מצמד תמונות שצולמו משתי זוויות צילום שונות במעט. צפייה בזוג של תמונות סטריאו המורכב משתי תמונות מונו-כרומטיות (תמונות "שחור-לבן" / תמונות ברמות-אפור) גורמת לתפיסה של תמונה תלת-ממדית מונו-כרומטית בעוד שצמד תמונות צבעוניות יתמזגו לתמונה תלת-ממדית צבעונית.

מערכות ראיה ממוחשבת ומערכות רובוטיות מונחות מרחוק משלבות אלגוריתמים המבוססים על מידע של צבע ועומק על מנת לשפר את יכולת ההתמצאות שלהם בשטח, ולשפר את יכולת גילוי המטרות שלהם. שילוב של מידע צבע ומידע עומק נפוץ במערכות אלו ויש יתרון בשילוב שתי שיטות אלו.

כאשר מוצגים לצופה שני גירויים ויזואליים השונים זה מזה בצורה קיצונית, לדוגמא, תמונה של בית בעין ימין ותמונה של פנים בעין שמאל, קשה למערכת הראיה למזג את התמונות לתמונה אחת ומתרחשת תופעה לא יציבה שנקראת Rivalry , תחרות בין שתי העיניים או בין שני הגירויים.

גירויים ויזואליים שונים בעלי תכונות שונות יכולים לגרום לתופעה לא יציבה זו. לדוגמא, הגירויים יכולים להיות שונים בתכולת האינפורמציה, שונים בתכולת הצבע (עיגול ירוק לעין אחת ועיגול אדום לעין השנייה), תמונות בקונטרסט שונה, בגודל שונה של אובייקטים ועוד.

מחקרים רבים חקרו את התופעה של תחרות הבין-עינית בהקשרים שונים והיא משמשת ככלי שבאמצעותו ניתן לחקור מבחינה ניורולוגית ופסיכו-פיסית את מערכת הראיה האנושית ולמפות אזורים שונים במוח מבחינה היררכית, פונקציונלית ותפיסתית. נבדקו פרמטרים שונים כמו השפעה של שינויים בתכונות של קונטרסט, תנועה שונה, קווים בתדירויות שונות ובכוונים שונים, רמות תאורה שונות ועוד, על משך הזמן שבו הגירוי יציב מבחינה תפיסתית. כמו כן, נבדקה השאלה האם תופעת אי- היציבות היא תוצר של תחרות בין העיניים או בין שתי הדמויות וכן נחקר הקשר בין תאוריית הדיכוי (suppression) ובין מנגנוני ה- Rivalry ועוד. מחקרים אלו מופיעים בספרות, והם משמשים בסיס לעבודות רבות בנושא Rivalry, כמו גם בנושאים רבים אחרים בתחום חקר הראיה.

מספר שאלות מחקריות עדיין נותרו ללא מענה: מה יקרה אם אחת מהתמונות הצבעוניות בצמד הסטריאוסקופי הצבעוני תוחלף לתמונת רמות אפור: האם תפיסת העומק לא תפגע למרות שמידע הצבע יהיה חסר באחת מתמונות הסטריאו? האם תתקבל עדיין תחושת הצבע?
עבודת מחקר זו נותנת מענה לשאלות מחקר אלו ומרחיבה את הבדיקה על תמונות מעורבות (MIX) תחת השפעה של פרמטרים נוספים כמו טשטוש, קוים מנוגדים בכוון ודחיסה.

לצורך כך בוצעו ניסויים פסיכו-פיסיים מבוקרים בקבוצת מחקר של נבדקים על מנת לתקף את ההיפותזה שצמד סטריאוסקופי, המורכב מתמונה צבעונית ומתמונת רמות אפור (שייקרא להלן "תמונה מעורבת" או באנגלית "MIX"), יוצר תחושה של תלת-ממד וצבע. הניסויים בוצעו על מספר סטים של תמונות סטריאוסקופיות בעלות תכולת צבע שונה ואובייקטים בגדלים ומרחקים שונים זה מזה.
התמונות צולמו באמצעות מצלמה דיגיטלית, המוסטת בכוון האופקי בלבד, כדי לרכוש שתי תמונות של אותה הסצנה משתי נקודות מבט שונות ולחקות את אופן הראיה הדו-עינית האנושית (binocular vision).
שתי התמונות הצבעוניות, השמאלית והימנית, הומרו כל אחת לתמונת רמות-אפור (תמונת שחור לבן) והורכבו ארבע קומבינציות הסטריאו הבאות:

1. צבע – צבע (שתי תמונות צבעוניות, מימין ומשמאל).
2. רמות אפור – רמות אפור (שתי תמונות ברמות אפור, מימין ומשמאל).
3. צמד מעורב: צבע – רמות אפור (כאשר תמונה צבעונית מוצגת לעין ימין ותמונת רמות-אפור לעין שמאל).
4. צמד מעורב: רמות אפור – צבע (כאשר תמונה צבעונית מוצגת לעין שמאל ותמונת רמות-אפור לעין ימין).

התמונות הוצגו באופן רנדומאלי לנבדקים באמצעות שני מכשירים:

- סטריאוסקופ (אלמנט הדמאה תלת מימדי פשוט, משנת 1905).
- HMD (Head- Mounted- Display), תצוגת קסדה המשמשת כאמצעי לראיה תלת מימדית ונמצאת בשימוש בעיקר ביישומים של עולם וירטואלי.

הנבדקים שהשתתפו בניסויים עברו בדיקת עיניים מקיפה ולא פולשנית. כל הנבדקים היו בעלי ראיית צבע תקינה, ראיית עומק תקינה וראיה מאוזנת בין שתי העיניים ונמצאו ככשירים להשתתף בניסוי. בנוסף לכל נבדק נבדקה העין הדומיננטית והיד הדומיננטית (שהוגדרה כיד המשמשת לכתיבה).
התמונות הוצגו לנבדקים מבלי שהם היו מודעים לתכולת הצבע של הצמד הסטריאוסקופי שהוצג להם. הנבדקים נתבקשו לדרג את תפיסת העומק ותפיסת הצבע של התמונה בה הם צופים בסולם שבין "1" ל-"10". כאשר לגבי תחושת הצבע ציון של "1" מתייחס לתמונת רמות אפור ואילו ציון "10" מתייחס לתמונה צבעונית. בתחושת העומק, ציון "1" מתייחס לתמונה "שטוחה" ללא עומק בעוד שציון "10" מתייחס לתמונה תלת ממדית.

ניתוח התוצאות העלה כי התמונה המעורבת נתפסה ע"י כל הנבדקים כתמונה צבעונית בעלת עומק. לא נמדדה ירידה בתחושת העומק וזוהתה ירידה קלה בלבד באיכות הצבע של התמונה התלת-מימדית המעורבת בהשוואה לתמונה צבעונית מלאה.
תופעה זו עקבית עם הממצאים שמנגנוני הצבע שמופקדים על עיבוד הצבע במוח אינם מרוכזים באזור אחד וקיימים שני מנגנוני צבע שפועלים בשלבים שונים במסלול הראיה. המנגנון הראשון מתבסס על מידע חד-עיני (מונוקולרי) ואילו המנגנון השני מתבסס על מידע דו-עיני (בינוקולרי).

אפקט של אסימטריה בתפיסת הצבע התגלה בצפייה בצמד המעורב. מיקומה של התמונה הצבעונית בצמד המעורב (תמונה צבעונית מימין או משמאל לתמונת רמות האפור) נמצא כמשפיע על איכות תפיסת הצבע של הנבדק. מתוך 15 נבדקים, לארבעה נבדקים לא נמצאה העדפה לצד של צבע, לשני נבדקים נמצאה העדפה מובהקת להצגה של צמד מעורב כאשר התמונה הצבעונית מוקמה בצד שמאל ואילו ל 11 נבדקים נמצאה העדפה מובהקת לצבע כאשר התמונה הצבעונית בצמד המעורב הוצגה להם לעין ימין.
כמו כן, נבדקה אסוציאציה בין העין המועדפת לצבע, לבין העין הדומיננטית ובין העין המועדפת לצבע לבין היד הדומיננטית, עבור כל נבדק. נמצאה נטייה של בעלי עין דומיננטית ימנית להעדיף תצוגה בתמונה מעורבת שבה התמונה הצבעונית מוצגת בעין ימין. נמצאה אסוציאציה מובהקת חיובית בין היד הדומיננטית לבין העין המועדפת לצבע. הסתבר כי כל הנבדקים בעלי עין דומיננטית לצבע ימנית היו ימניים מבחינת היד הדומיננטית. מבין שני בעלי עין דומיננטית לצבע שמאלית, לנבדק אחד הייתה יד שמאל דומיננטית ולשני יד ימין דומיננטית. מומלץ לחזר על הניסוי בקרב קבוצת מבחן גדולה יותר שבה מספר משמעותי של נבדקים בעלי יד שמאל דומיננטית שמאל.

כמו כן ידוע מהספרות, ששתי תמונות המוצגות כצמד סטריאוסקופי אינן צריכות להיות בעלות אותה חדות על מנת ליצור תחושת עומק. מחקרים קודמים הראו כי טשטוש של אחת מהתמונות בצמד סטריאו צבעוני או בזוג סטריאו מונו-כרומטי לא משפיע על תפיסת העומק שמתקבלת משתי התמונות.
בהתבסס על עובדה זו, נבדקה השפעת הטשטוש של התמונה המעורבת על תפיסת העומק והצבע. בוצע ניסוי עם קבוצת תמונות סטריאוסקופיות שתכולתן טושטשה בצד אחד או לחילופין בשני הצדדים. מתוצאות הניסוי עולה שכאשר תמונת רמות האפור בצמד המעורב מטושטשת, תפיסת העומק אינה נפגעת ואילו תפיסת הצבע משתפרת, בעוד שכאשר התמונה הצבעונית טושטשה תפיסת הצבע נגרעה.
בהמשך, בדק המחקר את תפיסת הצבע והעומק של תמונה מעורבת תחת השפעה של תחרות צורנית בין-עינית (Form Rivalry). לכל אחת מהתמונות בצמד המעורב הוסף אזור עם סריג של קוים אלכסוניים. בתמונה הימנית הוצגו קוים אלכסוניים הנוטים בזוית של 45 מעלות לשמאל ובתמונה השמאלית הוצגו קוים אלכסוניים הנוטים בזוית של 45 מעלות לימין. בניסוי זה, בנוסף על דרוג תפיסת העומק והצבע נשאלו הנבדקים לגבי הכוון שאליו נוטים הקווים של הסריג (ימין / שמאל / אין) . התוצאות העלו כי בזמן הצפייה בצמד הסטריאו כוון הקווים היה לא יציב, והנבדק חווה ריצוד בין שני כווני הקווים, בעוד שתפיסת העומק ותפיסת הצבע היו יציבות.

בהמשך לתוצאות שהתקבלו מהניסויים שבחנו את השפעת הטשטוש על התמונה המעורבת, שבהם הוכח שתפיסת צבע של תמונה מעורבת צבעונית משתפרת עם טשטוש תמונת רמות האפור, בוצעו במחקר ניסויים נוספים שבהם נבחנו שלוש שיטות דחיסה שונות של תמונת רמות האפור. שלוש השיטות היו: המרה של תמונת רמות האפור מייצוג של- 8 ביט לייצוג של- 6 ביט, שימוש בפירמידת תמונות גאוסיאנית (Gaussian Pyramid) וטשטוש עם מסכה בגודל של 3X3 פיקסלים. התוצאות הראו שהתופעה הבסיסית של תפיסת צבע ועומק בתמונה מעורבת יכולה לשאת דחיסה מסוגים שונים. בנוסף הראו התוצאות שלא נמצא הבדל בתפיסת העומק והצבע כתוצאה משלוש השיטות. יש לציין, ששלוש השיטות נבחרו על מנת לבחון את השפעת הדחיסה על תפיסת התמונה המעורבת, ולא במטרה להעדיף שיטת דחיסה אחת על אחרת.

המחקר המוצג בעבודה זו בודק את הדרישות המינימליות הדרושות לצורך צפייה בתמונה סטריאוסקופית צבעונית, מנקודת המבט הפסיכו-פיסית.
לתוצאות עבודת מחקר זו השפעה על יישומים שונים ויישומו עשוי להקל בהרחבת צווארי בקבוק קיימים ביכולת שידור או לאיחסון של מידע וידאו ושל סטריאו בצבע למשל, בשידור תמונת סטריאוסקופית. לצורך שידור ו/ איחסון של צמד תמונות סטריאוסקופיות צבעוני יש צורך בששה ערוצים של מידע צבע (שתי תמונות שמוצגות במרחב צבע כלשהוא: RGB, YIQ, וכו').
שימוש בשיטה המוצעת במחקר זה (תמונה מעורבת בעלת תמונה צבעונית אחת ותמונת רמות אפור) יאפשר תחושה של צבע ועומק, תוך כדי הקטנה של כמות הערוצים הנדרשת לצורך העברה, שמירה ו/או שידור של תמונת סטריאו צבעונית מששה ערוצים לארבעה ערוצים. בנוסף, ע"י תוספת של דחיסה ניתן עוד להוסיף ולהקטין את רוחב הפס הדרוש לצורך השידור הסטראוסקופי.

תוכן העניינים

עבודה זו נעשתה בהדרכתו של ד״ר גל קמינקא מהמחלקה למדעי המחשב
של אוניברסיטת בר-אילן.

תפיסה של תמונה צבעונית תלת-ממדית מצמד סטריאו המכיל תמונה צבעונית ותמונת רמות- אפור

חבור לשם קבלת התואר ״דוקטור לפילוסופיה״

מאת: טרמין יעל
המחלקה למדעי המחשב

הוגש לסנט של אוניברסיטת בר-אילן
י׳ בטבת התשס״ז