國 立 交 通 大 學

電 控 工 程 研 究 所

碩 士 論 文

利用 3D 顯示平台探討視調節微動與視覺疲勞之研究

Research of Accommodative Microfluctuations Caused by Visual Fatigue Based on 3D Display Platforms

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中 華 民 國 一百零一 年 十 月

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摘要

不同的色彩與影像表現對於人眼造成不同程度的視覺疲勞。本研究主要利用視調節微動之高頻成分頻譜功率(Spectral Power of High Frequency Component of Accommodative Microfluctuations)為客觀指標來進行視覺疲勞分析來探討顯示器色彩形成方法、3D顯示技術、光源以及個人差異對於視覺疲勞的影響，並利用問卷法做為主觀評估。其中顯示器色彩形成方法為分時形成法(Time Sharing Method)與空間組成法(Spatial Formation Method)；3D顯示為快門式眼鏡(Shutter Glasses)與偏光式眼鏡(Polarized Glasses)；光源為發光二極體之背光源(LED Backlight)與發光二極體(LED)與雷射二極體(LD)之混合光源。目前已知分時形成法有可能產生色分裂(Color Break-Up)使人眼容易產生疲勞。

研究中利用快閃式3D LCD TV、偏光式3D LCD TV與雷射投影機作為研究之對象。一開始受測者先進行辨色力測驗，觀看3D影片與2D影片進行人眼刺激於同一視距、不同觀看時間，在觀看顯示器前後均利用睫狀體調節微動分析儀紀錄受測者視調節微動情形並填寫主觀評量問卷。最後以變異數分析與t檢定來分析與比較。實驗結論為(1)3D影片給予人眼的負擔大於2D影片($p<0.001$)。(2)快閃式眼鏡造成的負擔大於偏光式眼鏡($p=0.012$)。(3)分時形成法給予的負擔大於空間形成法($p=0.008$)。(4)LED背光給予的負擔與LED與LD混光源無差別($p=0.162$)。(5)整體來說，辨色力普通者負擔大於辨色力較好者($p<0.001$)，而在觀看2D影片於LCD TV以及使用偏光視眼鏡觀看3D影片之後，兩者的視覺不適感程度一樣。(6) HFC確實可以客觀地評估視覺系統運作後生理上的緊繃及壓迫程度，進而評估視覺疲勞。

本研究已初步將不同色彩與影像的表現方法與視覺疲勞之關係建立出來，未來除了改變實驗中之參數進行更深入的研究，並將以前瞻即時監測裝置來實現，達成視覺疲勞之即時監測。

Research of Accommodative Microfluctuations Caused by Visual Fatigue Based on 3D Display Platforms

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Abstract

The appearance of different colors and images causes different levels of visual fatigue in the human eye. Research uses the spectral power of high frequency component of accommodative microfluctuations as a major objective indicator for analyzing the effects of visual fatigue through color formation methods, 3D display technologies, light sources and individual differences. A questionnaire is used as a subjective indicator. Color formation methods involved in the research are time sharing and spatial formation method, and the 3D display technologies use shutter and polarized glasses; Light sources are light emitting diode (LED) backlights and mixed LED and laser diode (LD) lights. So far the color break-up from time sharing method has been known to make human eyes tire easily.

This research used devices such as: a shutter 3D LCD TV, a polarized 3D LCD TV and a laser projector. Firstly, the subjects' color discrimination was examined by the hue test, and then, at another time, by viewing 3D and 2D videos at the same visual range to stimulate the eyes. Before and after the experiment the subjects' accommodative microfluctuations were measured by the auto refract-keratometer, and then a questionnaire was filled in. Finally the analysis of variance (ANOVA) and a t-test were used for analysis.

Conclusions are: (1) 3D videos afflict greater visual fatigue than 2D videos ($p<0.001$). (2) The shutter glasses afflict more visual fatigue than the polarized glasses ($p=0.012$). (3) Time sharing method afflicts greater visual fatigue more than spatial formation method ($p=0.008$). (4) There is no difference between the LED backlight and mixed LED and LD lights ($p=0.162$). (5) In general, people with normal color discrimination have more visual fatigue than those with the good ($p<0.001$), but the visual discomfort are the same on LCD TVs and polarized system. (6) The HFC can evaluate the physiological stress or strain by overexerting the visual system, which then leads to visual fatigue.

Rudimentary relationships have been found between different colors and images appearances and visual fatigue. However, more detailed research is required using different parameters, and visual fatigue could be monitored with the development of an advanced real-time sensor.

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Chapter 1 Introduction

As technology advances, many displays such as liquid crystal, projections display, plasma panels and 3D displays are used in our daily lives. Although enriching to the visual sense, various displays afflict eyes with symptoms such as dry eye, visual fatigue, eye ache and blurred vision due to drawbacks such as electromagnetic radiation and high luminance, and poor habits such as gazing at objects for a prolonged time or at short range. It is an important to find factors that cause visual fatigue in order to protect the eyes.

Currently visual fatigue is a common affliction because people frequently view displays for a long time. As these stimulate the eyes continuously, they also cause a great number of visual problems. Therefore, it is worth discussing the effects of such displays on people's vision.

From a visual standpoint, displays can be divided into three parts: color formation methods, 3D technologies and light sources. In a study on the effects of visual fatigue from various colors and images appearances it is necessary to find a stress-free way for people to view things. Methods involved in the research on color formation are time sharing and spatial formation; 3D displays use shutter and polarized glasses; LED backlights and mixed LED and LD lights are the lighting sources. To date, the color break-up from time sharing method has been known to cause visual fatigue in the human eye, and it is common for 3D displays to make people feel tired. The main focus of this research is to discover the effects of other factors.

To solve these problems, it is necessary to find a suitable indicator for evaluating the effects of various displays on the human eye. There are various indicators for evaluating visual fatigue. A subjective method such as a questionnaire could be used, and some objective method such as critical fusion frequency which is suitable to certain case. This study proposes to evaluate visual fatigue through accommodative microfluctuations of the ciliary body. There is now a similar evaluation method in medical research on visual fatigue called the high frequency component of accommodative microfluctuations. For instance, Gray *et al*. [1] used low frequency component (LFC) and high frequency component (HFC) to analyze visual variations after using visual display terminals. The HFC's spectral power was analyzed by Kajita *et al*.[2]. It showed that visual fatigue could indeed be measured and quantified. This method can effectively and objectively determine whether subjects are suffering from visual fatigue. Therefore, this research uses it as an indicator for studying the relationships between the color formation methods, 3D technologies, light sources, individual differences and visual fatigue.

For this research, the test was designed using 3D and 2D videos to stimulate the human eye under different modes. Two blue-ray DVDs were selected, with a 15 min viewing time, for each mode. Before the experiment, subjects were given a hue test to pinpoint individual differences, and then they were measured by the auto refract-keratometer (Speedy-K; Nikon, Tokyo, Japan). They would also complete a questionnaire, before and after the experiment (four times for each mode). The auto refract-keratometer was used to measure and record the subjects' accommodative microfluctuations, and then to calculate the spectral power of the high frequency component, a key point and major indicator in this research. It represents the state of the microfluctuations in the ciliary body, which decides whether or not subjects have visual fatigue. The differences between the before and after viewings are compared, using statistics, the ANOVA and a t-test to determine the relationships between these factors.

Chapter 2 Visual Fatigue

Different degrees of visual fatigue, a common affliction of present day society, occur in conditions where the eyes are used for a long time. Thanks to advancing new technology, information, whether it is dynamic or static, can be shown in displays. People usually watch all kinds of displays in their daily lives. External lighting and information stimulate each part of the eye continuously, causing problems such as visual fatigue, accommodation and a decrease in vision quality. Take computer use for example, according to the United States National Research Council in 1983, fifty percent of Americans feel uncomfortable when they use computers; moreover, ninety one percent of those computer users suffer from visual fatigue symptoms such as visual discomfort, blurred vision, double vision, tearing, myopia and so on [3]. So far, several devices and tests have been designed by researchers to measure visual fatigue and discover the reason for it. Now there is a need for further research to suggest ways to relax the eyes.

2.1 Visual Process

Vision is one of the most important sensory organs. People are able to see the world in color through their eyes. However, using one's eyes for long periods of time may easily results in visual fatigue. Therefore, before studying the problem of how displays cause visual fatigue, it is necessary to determine how color images and stereoscopic vision are generated in the visual system.

Fig. 2-1 shows how the eye's refractive and photosensitive system works when a light source illuminates and reflects an object. Light enters the cornea and continues into the pupil's aqueous humor. Just like the shutter of a camera, the pupil is controlled by the dilator sphincter. The sphincter papillae constricts or dilates from the intensity of the incoming light. After passing through the pupil, light is refracted by the crystalline lens. The lens curvature is controlled by the ciliary body; it has the ability to refract light and focus on objects, either distant or up close. Finally the light passes through the vitreous and the image is imprinted on the retina. The cornea, aqueous humor, crystalline lens and vitreous are the eye's refractive system. On the retina are cone and rod cells, the eyes photosensitive system that act as autoradiography films. Fig. 2-2 shows the electromagnetic spectrum's frequency band where human eyes can sense ranges between about 360 to 400nm (purple) and 780nm (red). Cone cells are the photoreceptor cells in the eye's retina. When luminance is above 3 nit it allows photopic vision [4]; it is divided into three types to sense light in three color bands, as shown in Fig. 2-3. The cones number around seventy million, with the total number of cells peaking close to 564-580 nm; 534-545 nm is about thirty times greater than 420-440 nm [5], so the human eye is more sensitive to yellow wavelengths of 580 nm. Rod cells, numbering about a hundred million, are photoreceptor cells when luminance is under 0.03 nit; they enable scotopic vision. A color image appears when the eye's refractive and photosensitive systems co-ordinate. Then stereoscopic vision is generated not only by the cells related to the retina [6, 7], but also by merging images from different angles in the brain. True stereoscopic vision is the result of the binocular and motion parallaxes, as shown as Fig. 2-4. The binocular parallax is the apparent difference in position of an object as seen separately by one eye, and then the other, which is then merged into a stereo image by the brain. Motion parallax is a depth cue that results from the motion of the head. As a result, people have stereoscopic vision.

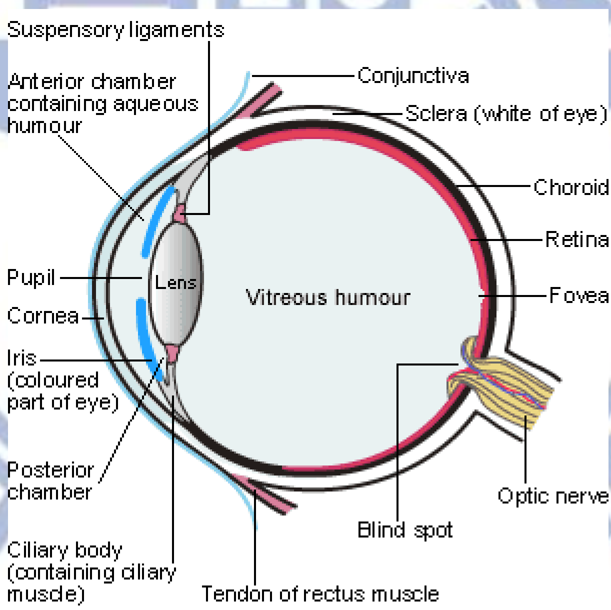

Figure 2-1: Anatomy of the eye [8].

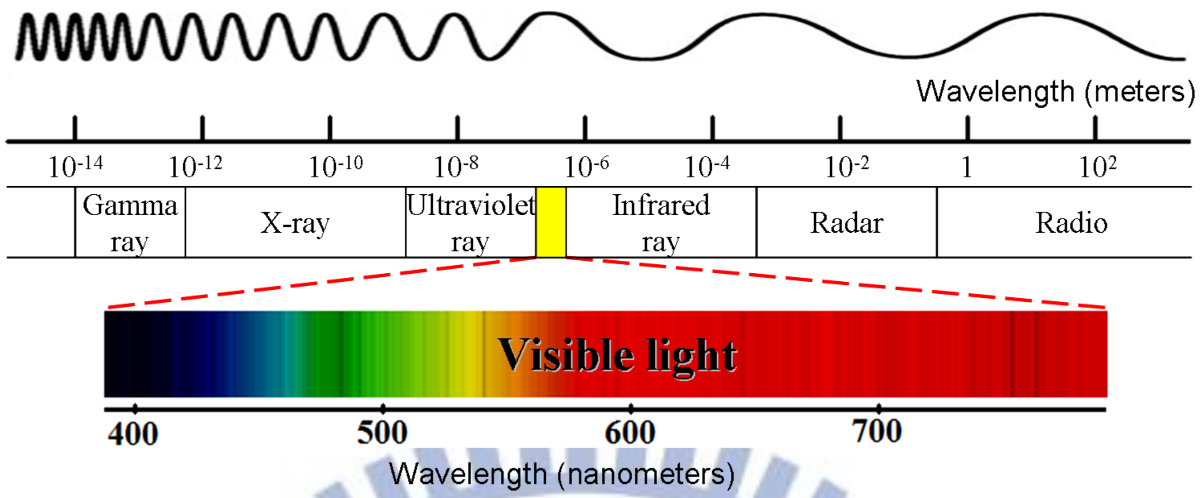

Figure 2-2: The perceive spectrum of human eye.

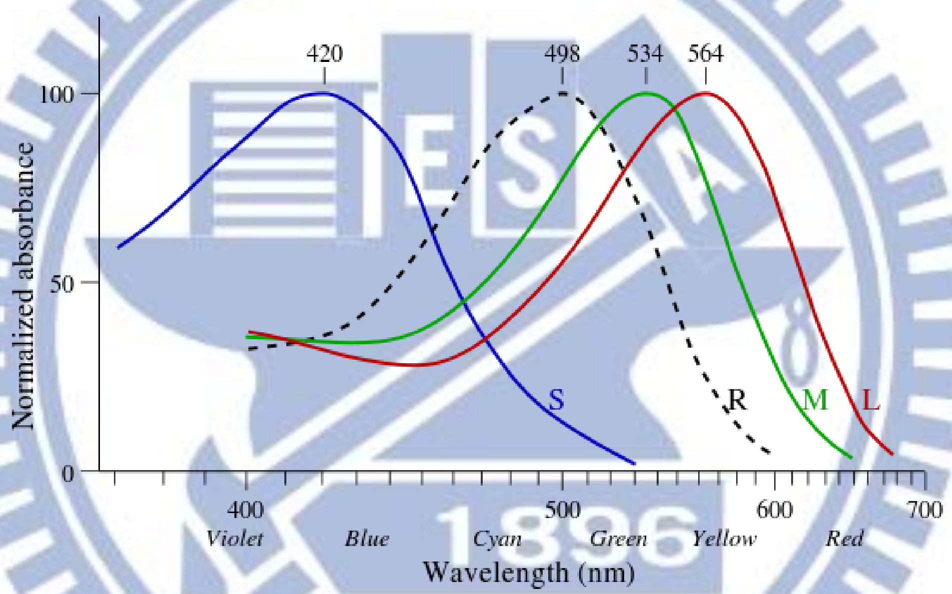

Figure 2-3: The spectra of human cone cells [9].

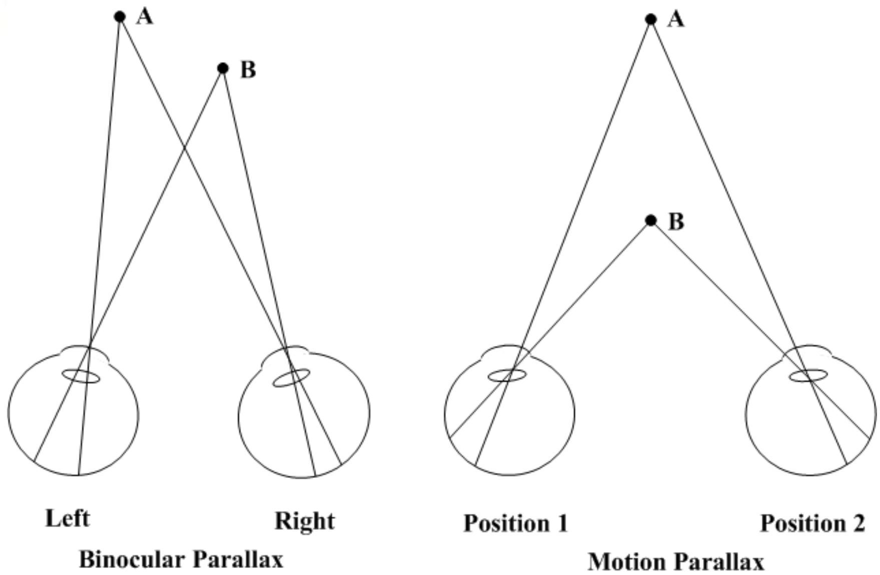

Figure 2-4: The binocular parallax and motion parallax.

2.2 Definition and Sources of Visual Fatigue

Visual fatigue, which contains various classes of expositions and definitions, cannot be summarized in just a single description. Megaw (1995) claimed that visual fatigue should be defined from all kinds of perspectives, and pointed out at least seven points describing visual fatigue: (1) Visual fatigue does not occur just anytime or anywhere. In circumstances where subjects receive visual stimulation from a repetitive task over a long period of time, they would suffer from visual fatigue. Moreover, if subjects have vision defects such as uncorrected refractory errors, visual fatigue occurs relatively quickly. (2) Visual fatigue should be distinguished from a task related to a mental workload, e.g., the task associated with the information and cognition demands. (3) People who suffer from visual fatigue can recover by resting or changing the working conditions. Also visual fatigue will not cause permanent injury unless the person suffers from some related disease. (4) Visual fatigue should be separated from the visual system's adaptive response. For example, the typical adaptation curve points out that upon entering a dark space, it takes the eye longer to adjust to the light, while in some conditions, the adjustment time is very short. The retina's neural adaptation takes only a few milliseconds in small luminance changes (Rushton and Westheimer, 1962). (5) Symptoms of visual fatigue are the main reason that visual fatigue exists. (6) Individual problems, visual tasks and the environment affect whether or not visual fatigue will occur, i.e., a person with uncorrected refractive problems like myopia or hyperopia, will feel uncomfortable and suffer easily from visual fatigue when asked to perform a visual task. (7) The visual fatigue symptoms do not always relate to vision, i.e., in a dry environment, dust particles can cause visual discomfort. Therefore, any factors that can affect vision may cause visual fatigue. These seven points give a general description and definition of visual fatigue. So by referencing them, one can determine whether or not visual fatigue actually occurs.

The source of visual fatigue is fairly extensive and, generally speaking, can be divided into three components [10]: (1) the Oculomotor control systems causes fatigue, i.e., accommodation control related to the ciliary muscle, the six extraocular muscles which regulate vergence control and balance, vision control associated with the same muscles relate to the pursuit and saccadic eye movements, pupil response by the dilator sphincter and the sphincter papillae, blinking associated with the orbicularis palpebrarum, and so on. (2) Neural processes: light entering the retina passes through the optic nerves and the lateral geniculate body through to the striate cortex. (3) Relatively non-specific effects like arousal levels and the amount of effort. Although visual fatigue is ascribed to three sources, they are obviously not independent. Alcohol or medications will reduce the arousal, affecting eye movements, such as causing rapid eye movements. Due to the recent surge in display technology, several studies focus on the influence of stereoscopic displays on visual fatigue. Some studies show the reasons that these displays cause viewers' visual fatigue; they are: (1) Abnormal binocular vision. (2) Dichoptic errors, such as geometrical distortions between the left and right images (e.g., depth-plane curvature, keystone distortion, crosstalk, and binocular rivalry). (3) Conflict between the vergence eye movements and accommodation. (4) Excessive binocular parallax [11-14].

After extensive overuse, various symptoms arise: (1) aching, burning, tearing, strain, irritation or dryness in the eye; (2) double vision; (3) headaches; (4) the decrease of accommodation power and convergence; and (5) a decrease in visual acuity, sensitivity to contrast and speed of perception. These are possible symptoms when people suffer from visual fatigue, but in reality there are probably more symptoms [12, 15-17].

2.3 Indicators and Methods for Measuring Visual Fatigue

In visual fatigue research, there are various and extensive indicators and measuring methods, which can be divided into five types [10][[18-21]: (1) the measurement of the oculomotor systems, e.g., eye movement velocity, accommodation power, convergence, viewing distance, pupil diameter, er and blinking; (2) the measurement of visual acuity, e.g., visual acuity, critical fusion frequency (CFF); (3) measuring the performance of visual tasks, i.e., recognition speed and error detection rate; (4) the report of asthenopia symptoms, and (5) brain activity measurements like functional magnetic resonance imaging (fMRI), magneto encephalography (MEG) and electroencephalography (EEG) for observing neural activity affected by visual fatigue, both temporally (MEG and EEG) and spatially (fMRI).

Among the eight most common and obvious ways cited in numerous research papers, are seven objective or subjective indicators according to Chi and Lin [15] from Megaw(1995) such as accommodation power, pupil diameter, visual acuity, eye movement velocity, critical fusion frequency, the subjective rating of visual fatigue, visual task performance, and brain activity measurements which is applied to few researches. The subjective rating for visual fatigue is an indicator related to a judgment on the subjects' level of visual fatigue; it will have more inaccuracies, while others have objective indicators according to the response of intraocular components or the visual cortex' neural activity. The following sections give brief introductions to the eight indicators.

2.3.1 Accommodation Power

Accommodation refers to the ability of the crystalline lens to adjust the curvature to an object as its distance varies. The principle is that the curvature is adjusted by the ciliary body so that objects can be clearly imprinted on the retina. A diopter is the accommodation's unit of measurement. W. Jaschinski-Kruza [22] reported that accommodation is connected to visual fatigue. Charman and Heron [23] claimed that microfluctuations exist in the ciliary body, which shows that accommodation can be evaluated whether or not the subjects suffer from visual fatigue. Sumio Yano *et al*.[11, 24] reported that there are apparent variations in the accommodative response after watching stereoscopic displays. Instead of measuring the crystalline lens' accommodation power by using specific stimuli, due to the lack of measurement methods early studies focused on measuring the accommodation time or the nearest point of accommodation. Aside from using the VDT near-point tester to measure accommodation, laser, infrared and polarized vernier optometry were also included. Subjects' accommodations should be measured before and after the experiment in order to record their response, which can then determine whether or not the fatigue occurs. Iwasaki *et al*. found that after an hour of viewing the test target, the accommodation time increases. Thereafter, subjects were tested on a visual experiment for fifteen min, and then their eye was stimulated by a distant refractometer target for two min. It was discovered that after comparing the before and after accommodative responses, that visual fatigue decreases as the ciliary body relaxes when looking at a distant object; this proves that accommodation is definitely related to visual fatigue [25].

2.3.2 Pupil Diameter

The iris must dilate or contract as a screen's intensity changes, so that the dilator sphincter is forced to act frequently. The depth of field increases as the diameter of the pupil contracts, which affects the eye's accommodation ability. Consequently, some research assesses the degree of visual fatigue by the changes in the pupil's diameter. By using records from infrared photography, Geacintov and Peavler (1974) observed that subjects' pupils do contract after watching continuous displays. Murata (1997) claimed that it is appropriate to use the changes in pupil diameter to assess visual fatigue [26]. Backs and Walrath (1992) confirmed that the pupil's diameter response is highly sensitive to processing information; however, Taptagaporn and Saito (1990) [27] considered that it is easy for exterior stimuli to change the pupil, i.e., brightness, subjects' emotions and difficulty in analyzing information. Every variable should be controlled. Whether the pupil's diameter relates to the subjects' fatigue is not clear; so the results are inconclusive.

2.3.3 Visual Acuity

Haider *et al*. [28] pointed out that after working uninterrupted with a VDT for three hours, subjects have transient myopia when looking at distant targets. Landholt rings were used to survey the vision changes in the test. The subjects' average vision obviously decreased from 1.08 to 0.82, and the range became wider as the time was increased. Apart from the loss of vision, some researchers claimed that sensitivity also decreases. Perhaps fatigue in the oculomotor control systems is responsible for the loss of vision, e.g., accommodation or vergence systems relating to the lens' accommodation ability, a lowering of sensitivity in the vision process, or a general reduction in arousal. Therefore, the loss of vision, which is right for evaluating overall visual function, can also be used to evaluate visual fatigue. Besides using the Landholt rings to test eyesight, and asking and answering questions, some specific instruments are also available, such as the vision tester (OPTEC 2000, Stereo Optical) for example. The optotype inside the instrument is designed to employ the Landholt rings design concept. When doing research, eyesight should be tested before and after the experiment by the optotype. The test's design can also stimulate eyes efficiently and the visual acuity, from watching these stimuli, can be observed and compared.

2.3.4 Eye Movement Velocity

Six extraocular muscles regulate the movements of the eye. These movements can be recorded several ways and are generally divided into five methods according to the way the eye moves: (1) Electro-oculography, which puts electrodes around the eyes and records potential changes in the corneoretina. (2) A Video-Based Eye Tracker, which videotapes the subjects' eye movements. (3) A Scleral Search Coil, which assesses eye movement by using the electromagnetic induction theory. (4) The Dual Purkinje Image Tracker that uses different corneal refraction angles and lenses to shoot the pupil's contour. (5) Infrared Oculography uses infrared rays to irradiate around the iris, and reflex back. The optic signals are transferred into electrical impulses so that the eye movements can be understood by the signals. Bahill and Stark [29] pointed out that eye movement parameters will be influenced by the saccadic eye movement control system. As the intraocular and extraocular muscles control eye movements, over time it would cause muscle fatigue. After studying the saccadic eye movement system, Saito *et al*. [30] found that, for VDT staffs, the eye movement amplitude and frequency are high after work as opposed to before work. Hallett [31] noted that eye movement velocity is the function of the saccadic angle (the amplitude of vibration) and movement frequency. In other words, eye movement velocity is equal to the saccadic angle shifts multiplied by the frequency. When the saccadic angle is large, it will cause excessive torsion, which presses on the optic nerve or leads to conjunctivitis, so the eyes will hurt or be hurt. Schmidt, Abel, DellOssen & Daroff (1979) and Stberg (1980) claimed that eye movements could be used to evaluate visual fatigue because the reaction is obvious, especially for the ciliary body, so a visual fatigue study using eye movement velocity would be reliable.

2.3.5 Critical Fusion Frequency

Critical fusion frequency is a kind of temporal measure that enhances the flash frequency little by little. When subjects are looking at a flash of light, they feel it is continuous. In other words, the subjects fail to identify whether or not the light flashes. This flash of light reaches a critical point, which is called a critical fusion frequency. Analyzing the change in CFF is highly sensitive and suitable for assessing whether or not visual fatigue occurs. The CFF can be tested by using an instrument, (e.g., Handy Flicker, NEITZ), containing an optotype with different colors. The flash frequency can be gradually increased until the subjects feel that the optotype does not flash anymore; then the frequency can be recorded. This action can be repeated with decreasing frequency to observe whether or not the subjects' CFF also tends to decrease t [32]. Osaka [33] noted that when a VDU task shows any large red or blue words, both the foveal and peripheral CFF test show deterioration. Iwasaki *et al*. [34] studied the reactions of different CFF colors, and found that yellows and greens decreased after thirty min, and the red after fifteen. The distinction between color and light are provided by the cone cells and the rod cells, respectively, on the retina. Therefore, a decrease in the CFF represents a decrease in the retina's function. For the work place, the brightness contrast is best from between 7:1 to 11:1. The lower the light, the more fatigue people feel. In low brightness contrast, the decrease in the degree of CFF is fairly obvious.

2.3.6 Visual Task Performance

Many researchers prefer to observe if subjects suffer from visual fatigue by using direct or indirect visual performance measures. Aside from the reading [35] and simulated inspection tasks [36], there are some experiments that have been designed specifically for this purpose. This kind of indicator evaluates the subjects' visual response under different working conditions by comparing the before and after variation, so the degree of visual fatigue can be better understood. Nonetheless, there are three restrictions: (1) the drop in performance may not be caused by visual fatigue, e.g., it may be caused by boredom, low arousal or low spirits. Therefore, anything that can lower the visual performance should be avoided in a test so that there is nothing to connect the visual fatigue with the visual performance. (2) Perhaps performance is hindered by the subjects' special effort or learning, so using something that can be learned or achieved through effort should also be avoided. (3) Do not use methods that are difficult to attain, e.g., analyze the data before and after reading to determine the occurrence of visual fatigue from the reading speed and comparison of the error detection rate. Generally speaking, researchers like to observe whether or not the subjects with visual fatigue maintain the same performance levels after the experiment. Studies have shown that people who read monitors have a higher level of visual fatigue than those who read paper. As the visual fatigue increases, the reading efficiency is affected, either directly or indirectly. The research on multimedia dynamic information displays [37] showed that information load and speed of movement evidently influence visual performance measures and visual fatigue.

2.3.7 Subjective Rating of Visual Fatigue

Numerous researchers adopt the subjective rating method, which Sinclair [38] divided into five areas: rankings, questionnaires, interviews, ratings and checklists. Bullimore *et al*. [39] claimed that the advantage to adopting a subjective rating method for evaluating visual fatigue and visual performance measures is that it is easy to manipulate, involves little cost and is quick to evaluate, even if there are too many variables. The subjective rating method possesses higher sensitivity, but because it acts upon the subjects' subjective senses, its diagnostic, validity and reliability are still up for discussion. The cause of fatigue is hard to find. Other objective evaluation indicators should be involved when evaluating visual fatigue in order to improve the diagnosis. The most general method to determine the degree of visual fatigue is through a questionnaire. Researchers have to design a form where relevant visual fatigue symptoms can be recorded. Subjects rank their symptoms on the form in five to seven points [11, 26, 32, 40], according to their situation before and after the experiment. Afterwards the researchers use the total for after the experiment minus the one before, and then the occurrence of visual fatigue can be analyzed. There is another method that uses points for individual symptoms which occur, after watching the display minus the ones from before so that the strongest and the weakest symptoms can be compared.

2.3.8 Brain Activity Measurements

All perceptions and high-level recognition are processed in the brain. Therefore, any visual fatigue occurring after the experiment is reflected by new activity in the brain. Apart from providing variations in brain activity, brain activity measurements also provide understandable perceptual and cognitive processes to characterize variations of pathology, such as specific visual deficiencies. In order to achieve high sensitivity and specificity, high-quality spatial information, such as functional magnetic resonance imaging (fMRI) can be combined with high-quality temporal resolution, such as magneto encephalography (MEG) and electroencephalography (EEG). Most of the relevant brain activity studies on depth perception focus on basic issues like establishing the binocular vision's real path. Some visual fatigue studies have used this method to discuss the relationship between perception and the causes of visual fatigue. Emoto *et al*. [12] measured visually evoked cortical potential with an EEG, which reflects fatigue of the relevant intraocular muscles, extraocular muscles and nerves in the brain, and used a P100 latency (positive component at approximately 100ms latency) as a fatigue index. The delays for temporally changing parallax were significant, and a high correlation was found between the relative vergence limits and P100 latencies. In preliminary research Hagura *et al*. [41] use an fMRI combined with an MEG as a tool to measure visual fatigue, which allows the dipole data obtained by the MEG to be superimposed onto a 3D model set up by the fMRI. Although the results showed that the back left side of the brain was active while viewing stereogram and isocontour maps, the dipole activity varied with different watching periods, and the maps were not clear enough to identify and locate those exact areas; therefore, this method's applications need further investigation.

2.4 Comparisons of indicators

Overall, not all of the visual fatigue measurement indicators are high in sensitivity or obvious in every experiment. There are different restrictions or conditions in the different experimental environs [15], as shown as Table 3-1. The eye movement speed and pupil diameter are more obvious reactions, as they are highly sensitive in experiments containing dynamic information. These will fail to underline the variations if the experiment condition is static. Accommodation, eyesight and critical fusion frequency are highly sensitive in a long-term stimulated environment, but not obvious over a short period of time. C. F. Chi and F. T. Lin [15] pointed out that using these three indicators to evaluate visual fatigue will improve sensitivity if the test time is over sixty min. In order to improve validity, there is a need to increase both the viewing time and the number of subjects when adopting these three evaluation indicators. A subjective rating method can reflect all kinds of conditions that cause visual fatigue. The benefit of it is that it is easy to practice and has high validity, but it relies on the subjective element, and aside from consulting professional ophthalmologists or clinicians to enhance its validity, more samples and experiments are required. Information is displayed on monitors everywhere now, so there are many factors that lead to visual fatigue. To evaluate visual fatigue, different types of work need to be evaluated using different scales, so that the occurrence of visual fatigue can be found quickly and efficiently. Measuring brain activity is a pioneering method. A breakthrough in technology is required in order to achieve clarification and accuracy in locating and identifying visual fatigue by this method. Follow-up studies should continue to improve this method's validity.

An appropriate evaluation indicator should be chosen to investigate the relationship between the color formation methods, 3D technologies, light sources and visual fatigue. This indicator needs to satisfy every condition to compare these relationships. This study uses dynamic information as the experimental tool since displays are used to show the dynamics of daily life. The moving frames stimulate eyesight. Moreover, it is better to use multiple visibility ranges than others that just explore the influence of different ranges at short distances. From the eight indicators mentioned in the previous section for evaluating visual fatigue, accommodation and critical fusion frequency are highly sensitive at short distances and low brightness contrast respectively; both are unsuitable. Secondly, the pupil’s diameter is so easily influenced by exterior stimuli that it is difficult to control variations. The speed of eye movements can be adopted in a dynamic environment, but existing measurement methods are limited. Some instruments cause the eyes discomfort, and the measurement of movement time is inaccurate. Because of such difficulties, this study has not adopted this method. Visual performance measures have too many limits to operate, so it does not figure highly on the list. Lastly, eyesight evaluation conforms to the study’s goals; however, the stimulation takes a lot of time. As for brain activity measurements, due to the difficulty and uncertainty with equipment, it is not on the list. As a result, a subjective rating method is selected as one of the reference methods, the benefit being that it is easy to use in various conditions. In addition, to the subjective rating method, the study will use an advanced evaluation method of visual fatigue. This method uses microfluctuation variations in the ciliary body after it is stimulated to determine if visual fatigue occurs. This method analyzes how the ciliary body’s response to objects is different from accommodation. Because this indicator is not restricted by the conditions and relates to the subjects’ physiology and the ciliary body microfluctuations, it was adopted in this study, in addition to the subjective rating method.

Table 2-1: The comparisons of eight indicators.

Indicators	Advantages	Disadvantages
Accommodation power	High sensitivity to near work	Long time for stimulation
Pupil diameter	High sensitivity to dynamic condition	Unsuitability for static condition and many limitations
Visual acuity	Suitability to evaluation of whole visual system	Long time for stimulation
Eye movement velocity	High sensitivity to dynamic condition	Unsuitability for static condition and limitations of device
Critical fusion frequency	High sensitivity to contrast work in low brightness	Long time for stimulation
Subjective rating of visual fatigue	High face validity and easy applied	Low objectivity
Visual task performance	Direct and indirect show of visual fatigue	Many limitations to apply
Brain activity measurements	Understandable perceptual and cognitive processes to characterize the variation of pathology	Inaccuracy identification and locating

Chapter 3 Accommodative Microfluctuations

The eye lens' curvature changes its dioptric ability to maintain a clear image of objects as the distance varies. This self-adjusting mechanism on optical system calls accommodation, which varies from 0.01 m (10 D) to infinity (0 D) for normal and young eyes. The ciliary body around the lens controls the curvature of the lens by contracting and relaxing, and has a large number of suspensor ligaments connected to the lens. Theoretically, the ciliary body should be in fixed state when looking at an object, but actually it adjusts repeatedly instead of adjusting immediately to a suitable curvature during the accommodation process. In time, it becomes unstable and fluctuates with changes lower than 1 D and a frequency up to a few Hz. These are called accommodative microfluctuations [1, 2, 23, 42-47]. As people with normal vision look at a close object, the activity of the ciliary body is relatively low when compared to viewing a far object. When people with visual fatigue look at a far object, the activity of the ciliary body is significantly higher compared to normal vision, and remains high while looking at short distances, but is not as obvious compared to people with normal vision [2, 43]. When reading at short distances, people with myopia exhibit a significant increase in the power of accommodative microfluctuations [48].

3.1 Phenomena of Accommodative Microfluctuations

Collins (1937) [49] used an infrared optometer to measure patients and found that high frequency fluctuations occurred during accommodation. Since then, there have been a series of studies on this phenomenon. Arnulf *et al*. indicated that the fluctuations make images on the retina focus poorly. In the research, the double-pass ophthalmoscopic method was used to take pictures of retina images while subjects watched stable targets. The results showed that a series of adjustments let the ciliary body keep a balanced position while the amplitude is about 0.1D, which maintains an optimum response between the lens and the image but changes the contrast of the retina image further. As technology advanced, Campbell [50] developed a high-speed infrared optometer which has a high temporal resolution to record accommodative microfluctuations almost continuously, and can both quantify and establish a frequency domain for the microfluctuations [2, 23, 46, 51]. These microfluctuations act as the sinusoidal wave [2] and are defined according to two components: low frequency component (LFC) and high frequency component (HFC). Because the fluctuation frequency of about 5Hz is stable, the fluctuations above 5Hz are not adopted. The root mean square (rms) of amplitudes below 5Hz ranges between 0.02D to 0.2D [44]. Some research has reported peaks in the HFC [49, 50, 52, 53]. In addition to the classical IR autorefractometer, a wave-front aberrometer and ultrasound have also been used in the research. Wave-front recording accommodation can compute high order aberrations, like Zernike polynomials. So beyond spherical defocus and astigmatism [54, 55], additional information is available on the eyes' optics to analyze the microfluctuations and yield a total defocus error. The Ultrasonographic method, which is completely different from other optical methods, can track microfluctuations by measuring variations in the eye's morphology [56, 57]. Finally, an IR autorefractometer will be introduced in section 3.5.

3.2 The Power Spectrum of Accommodative Microfluctuations

The behavior of accommodative microfluctuations is complex, without rules and nonlinear in time; however, regular patterns exist while transferring the waveform into the frequency domain. According to the waveform, accommodative microfluctuations consist of two components: low frequency component (LFC) and high frequency component (HFC); the former is defined below 0.6 Hz and the latter between 1.0 to 2.3 Hz [1, 2, 23, 44, 45]. Accommodative microfluctuations may be affected by a distance of target [43, 58-60], pupil diameter [47, 61-63], the form and contras of target [64, 65], the luminance of target [1, 66, 67], the eye's age, astigmatism [68],visual fatigue [2, 43, 69, 70] ,bi/monocular observation of the target [62, 69], and artifacts such as cardiopulmonary signals [52, 71, 72] or other rhythmical physiological systems. Neurological control also affects the LFC's wavelength, and arterial signals correlate highly to the HFC [1, 44].

3.3 Relationship between Accommodative Microfluctuations and Visual Fatigue

Among the factors mentioned in section 3.2 that influence accommodative microfluctuations, the effect on the pupil's diameter is the most obvious. The pupil changes with light, and when the diameter is smaller, the HFC fluctuations are imperceptible, although the LFC increases; when the diameter increases, the HFC fluctuations become obvious and the LFC decreases [44]. Geacintov and Peavler (1974), Goldwater (1974), and Ukai *et al*. (1997) reported that there is a connection between pupil instability and visual fatigue [1]. Some recent research has studied eye variations and visual fatigue after viewing VDTs; it indicates the close connection between the pupil's variations and accommodative microfluctuations [1]; it showed that patients with asthenopia can indeed be diagnosed from changes in the HFC [2]. Table 3-1 shows that the HFC range for people with normal vision is about 40 to 60 while viewing a stable target at about 0 to -0.75 D, and that with asthenopia, it is about 60 to 70; the difference is imperceptible if the target is about -1.0 to -3.0 D. Suzuki *et al*. (2001) [43] tried using a color code to show the position of targets, the accommodative response amplitude and the HFC value as figures. While viewing a distant, stable target, Fig. 3-1 shows that a normal subject's HFC is about 50 to 60, labeled in green, while Fig, 3-2 shows a subject with asthenopia is above 60, labeled in red. After combining these results, it is concluded that the ciliary body's tension is low when viewing far objects, so its variation is large if visual fatigue occurs, and slight with short distances. Thus, the ciliary body's tension is recognized by the HFC variations and subjects are assessed to see if they suffer visual fatigue.

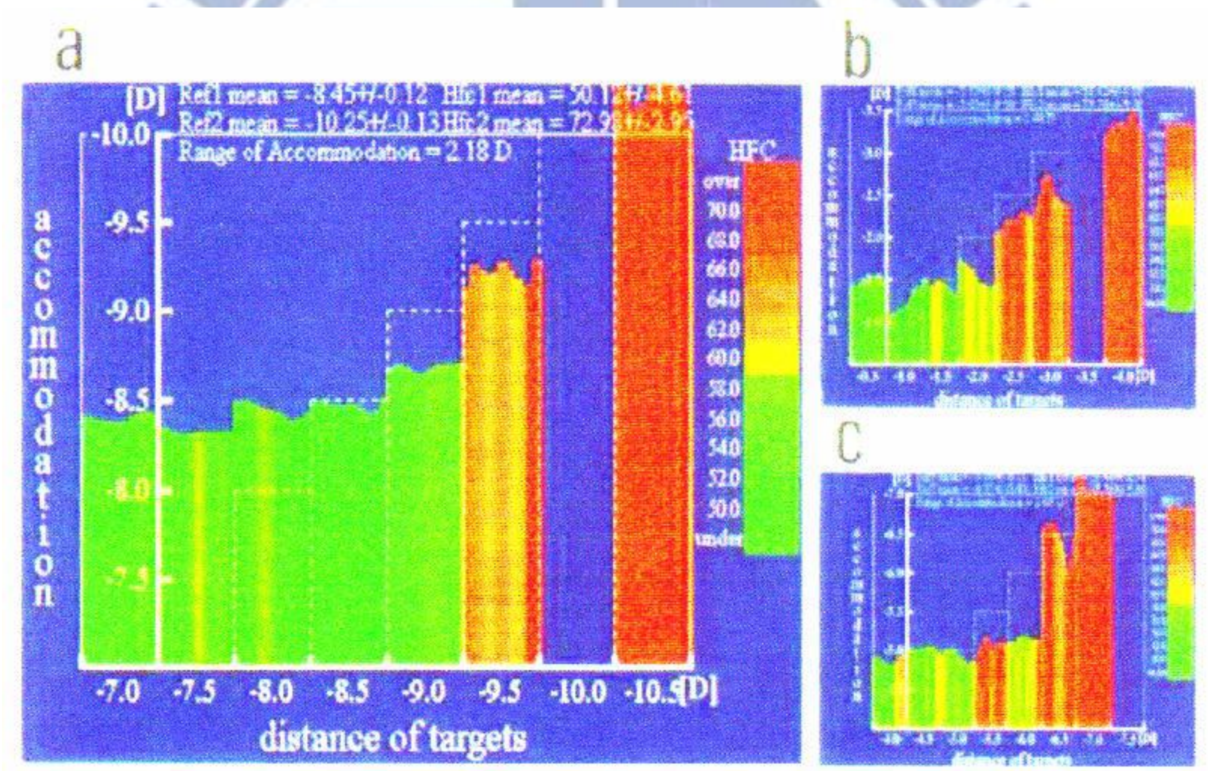

Figure 3-1: The HFC of normal subjects [43].

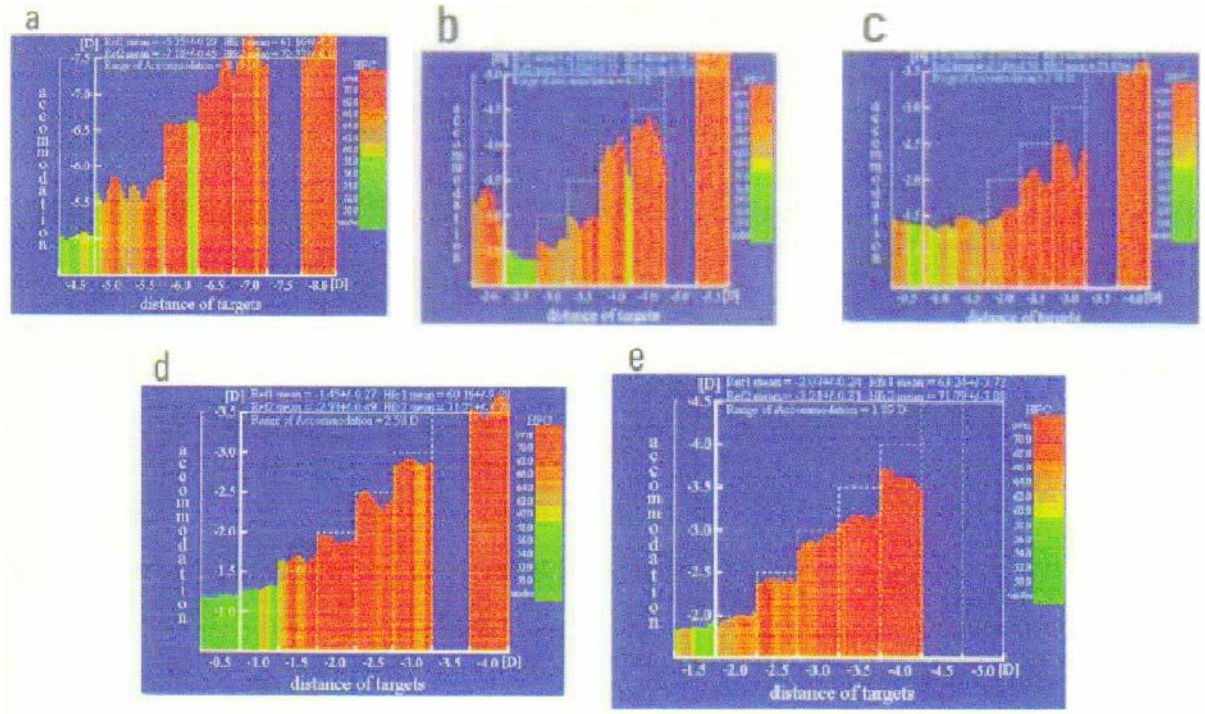

Figure 3-2: The HFC of subjects with asthenopia [43].

Table 3-1: The HFC of subjects in different distances of target. The "-" means no fatigue; the "+" means fatigue [2].

Subject	HFC1 (0~-0.75D)	HFC2 (-1.0~-3.0D)	fatigue
1	49.8	69.0	-
2	56.6	71.2	-
3	54.4	72.6	-
4	64.8	77.0	+
5	65.2	70.4	+
3	62.4	71.1	+
7	60.7	69.7	+

3.4 Automatic Refractor-Keratometer

In section 3.3 Dr. Kajita used the HFC to evaluate the state of visual fatigue by measuring the accommodation of different subjects, and Suzuki proved that the HFC values reveal if subjects suffer visual fatigue. So in 2003 and 2005, Dr. Kajita published two patents, for the auto refract-keratometer design (Speedy-K; Nikon, Tokyo, Japan) developed from his research. Fig. 3-3 shows infrared illuminated optotype that the auto refract-keratometer measures and records the eye's accommodative microfluctuations with in real time. A stepper motor controls the target distance. The relative position between the target and the optical lens changes when the motor steps, so subjects are stimulated by multiple distances during the measurement process. The chopper and receiver in the device sample the target's stimulation; the sample rate can be modified depending on the requirements. In order to acquire a large sample of accommodative responses and calculate HFC values, an auto refract-keratometer was applied in this research. There were 8 target distances in the device: +0.5D, 0D, -0.5D, -1.0D, -1.5D, -2.0D, -2.5D and -3.0D, from far to near. 0D means 6 meters in Optometry where the accommodative response is very low, and +0.5D is above 6 meters where the ciliary body is almost unadjusted so the image is blurred to the eye. The device used in this research features the Speedy-K Ver. MF-1 software that communicates with RS-232 and calculates the HFC; therefore, the subject's HFC can be analyzed and shown on the software interface.

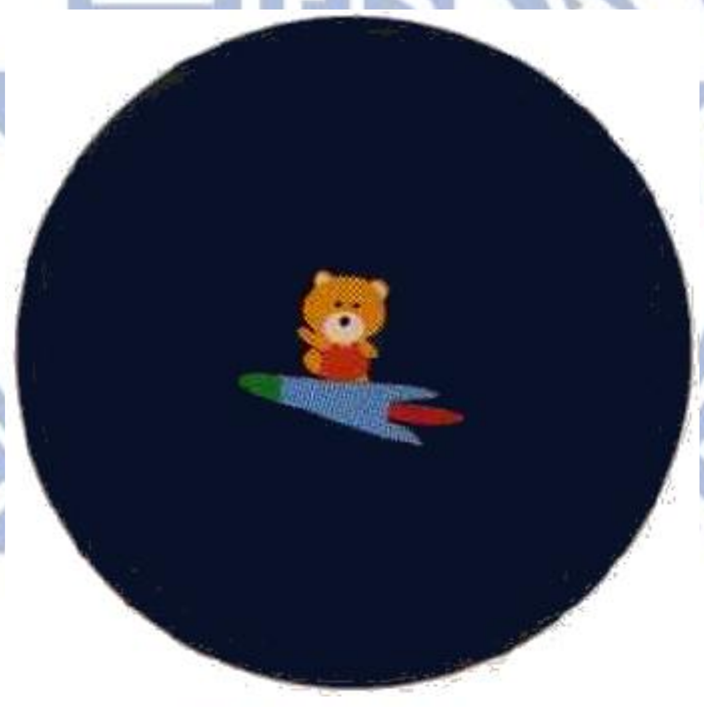

Figure 3-3: The target in the auto refract-keratometer.

3.5 Comparisons between the HFC and other Indicators

The indicators for evaluating visual fatigue, accommodation power, pupil diameter, visual acuity, eye movement velocity, critical fusion frequency, subjective rating of visual fatigue, visual task performances and brain activity measurements, have their own limitations. For instance, accommodation power is best used to evaluate visual fatigue because the lens curvature becomes larger in close work and fatigue occurs over long periods of time. Work station illumination is different from that of a target or dynamic information, and the iris' sphincter muscle, as a pupil constrictor, has to control the amount of light entering the eyes. Because it is easy to feel tired when working long hours, the pupil's diameter is a suitable evaluator under these conditions. The disadvantage to a subjective rating, is that the method's objectivity depends on the subjects' psychological and physiological feelings, rating it inadequate. So it is generally only used to supplement other methods.

The HFC is part of the accommodative microfluctuations spectrum, and is calculated according to accommodation records. Section 3.2 shows the high correlation between the HFC and cardiopulmonary signals; therefore eyes suffering from visual fatigue can be evaluated by the HFC variations because physiological aspects influence cardiopulmonary signals. In addition to measuring accommodative microfluctuations and calculating the HFC, the device can be used to measure accommodation power, which is more functional than optometers in the past.

The HFC is a speedy and uncomplicated indicator to evaluate visual fatigue. Although there is little research on visual fatigue with the HFC due to the expense involved in using the device, it can test a subject's level of visual fatigue.

Chapter 4 Methods for Color and Image Formation of Displays

Currently, people use electronic devices frequently in their daily lives. As technology has developed, people have continued to pursue more realistic and natural imagery, from the monochromatic television of thirty years ago, to color televisions using color filters, to the high quality lightweight televisions of today. In order to provide an advanced visual feast, technology has expanded into the 3D field. Various 3D displays are developing in stereo.

From a visual standpoint, displays involve three aspects: color formations, 3D technologies and the selection of light sources. Different display methods cause different sensations and effects on the human eye. This research uses two kinds of 3D liquid crystal display (LCD) televisions and a laser projector. The color formation methods, 3D technologies and light sources are introduced and detailed in the following sections, and a final comparison is given on each aspect's differences.

4.1 Color Formation Methods

Instead of binary images, color images have become the main method of displaying color filters, separating the light by a range of wavelengths. Three methods are based on these configurations: time sharing, spatial formation and an overlay formation method, each with its own expression in time and space. To date, all of the color displays being sold are manufactured by these methods. Time sharing is discontinuous in the time domain. Different colors like RGB are projected as time-sharing; in other words, they are discrete [73]. When a series of colors are projected in an interval shorter than the persistence of vision threshold, human eyes sense a color mix spatially, instead of three distinct colors, as shown as Fig. 4-1. Spatial formation method is discontinuous in spatial domain, where a pixel is made up of different color filters called a geometrical sub-pixel, like RGB filters. Although it is discontinuous due to gaps in the geometrical combination [73], eyes sense a color mix of three sub-pixels instead of recognizing their position and color if the color filters geometrical combination is close enough to the eyes' critical spatial resolution, as shown as Fig. 4-2. The overlay formation is an additional colored science principle that produces any color by projecting different colors like RGB in the same place. Since eyes cannot differentiate between original colors, a single color forms in the visual cortex [73], as shown as Fig.4-3. The laser projector used in this research applied the Digital Light Processing (DLP) as its time sharing method, and the two kinds of 3D LCD TVs applied the spatial formation method, which are detailed in the following sections.

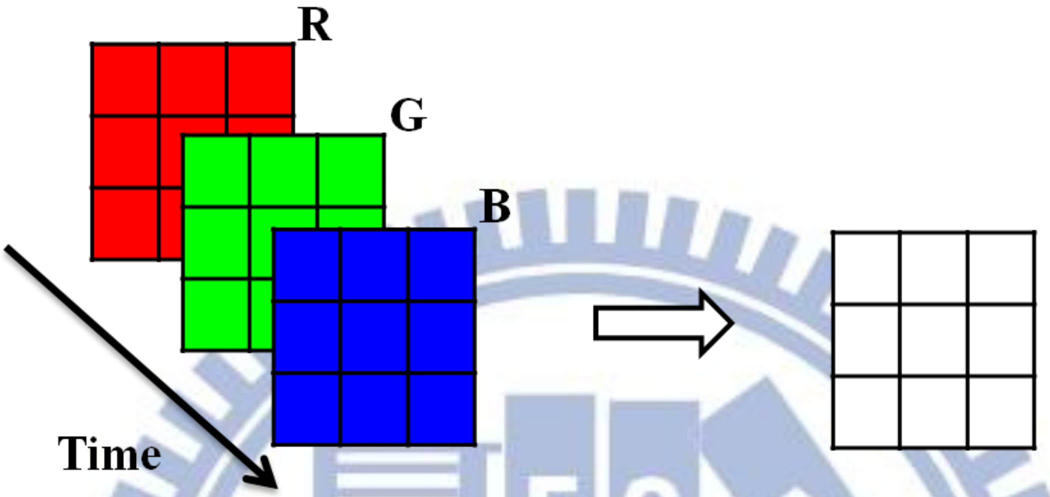

Figure 4-1: The concept of time sharing method.

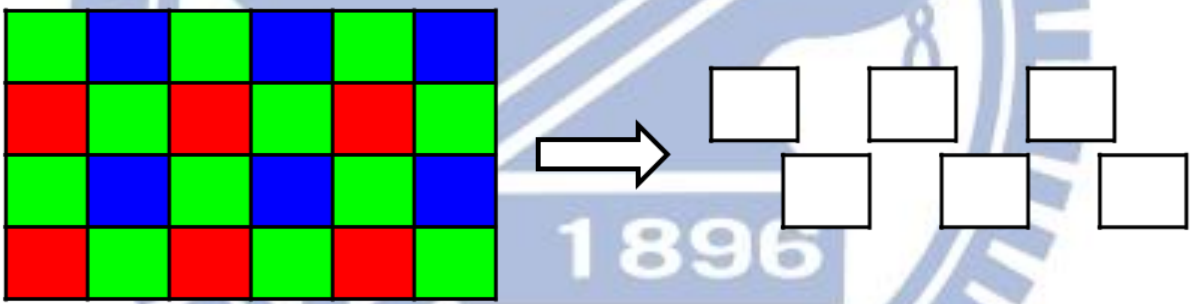

Figure 4-2: The concept of spatial formation method.

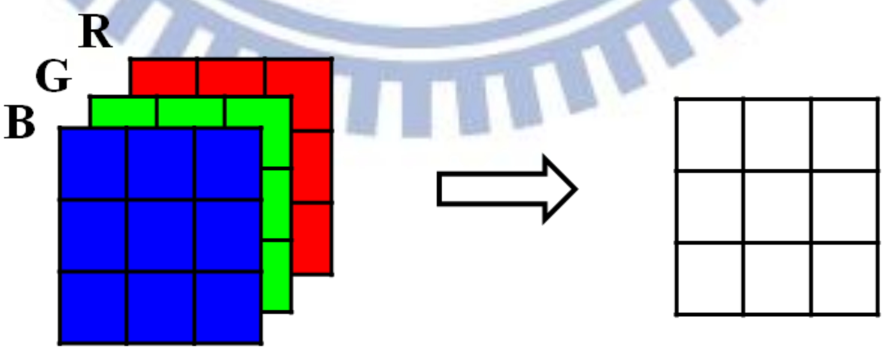

Figure 4-3: The concept of overlay formation method.

4.1.1 Digital Light Processing

Humans can observe a world of color through their eyes. We all know that we cannot see anything in a dark room because everything we see reflects light from a light source.

Digital Light Processing (DLP) is a projection technology developed by Texas Instruments, which outputs digital optical pulses with high optical efficiency after receiving electrical signals. As optical pulses pass through the eyes, they are converted into analog color images. DLP projectors based on the number of Digital Micromirror Devices (DMD), as shown in Fig. 4-4, are divided into single-chip, two-chips and three-chips. A single-chip is common in schools, homes and companies, while the two and three chips are usually reserved for specific situations such as a movie theater, due to the costs and large volume. There are two important components in the single-chip optical system, the color wheel and the DMD.

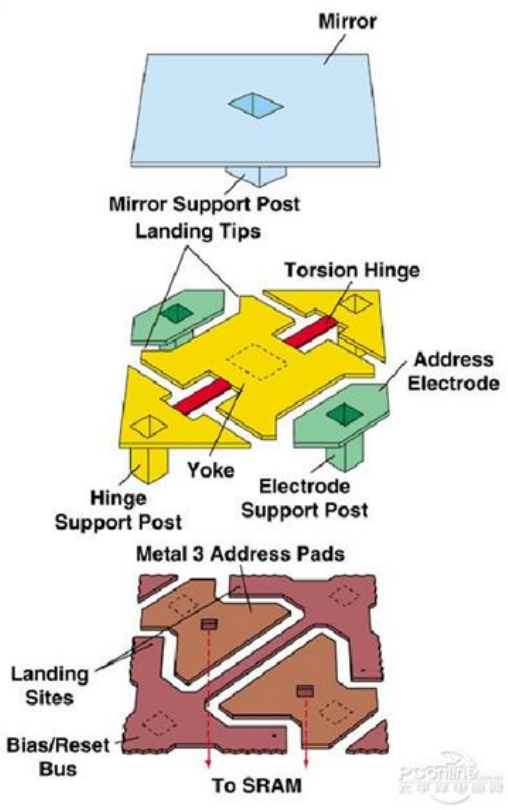

Figure 4-4: The structure of DMD [74].

A color wheel is a circular sheet with red, blue and green color filters. Using various wavelengths up to 60Hz can provide 180 color fields per second. When a white-light source passes through the color wheel, red, blue, and green images are formed in the eyes, but the light's intensity decreases as the spectrum is filtered. The DMD is a quick optical switch that is the core of DLP projection technology. Many micro mirrors reflect the colors as they pass through the lens to the color wheel, and an image is projected onto the screen. Input signals are written sequentially and converted into RGB data in the DMD's static random access memory (SRAM). The white-light source focuses on a color wheel by focusing the lens' images on the DMD. As the color wheel rotates, red, blue and green are sequentially projected onto the DMD. Thus, when red is emitted on the DMD, mirrors decide when to switch the position and display intensity from the R data, to blue and green. Video signals are the same. The human visual system combines sequential colors to get a color image [75].

The color wheel design concept is time-sharing; it reveals color in a rotational frequency quicker than the human eye. However, some people with sensitive vision see three individual colors so their visual quality is affected. This is called color break-up (CBU) or a rainbow effect [76-79] , shown as Fig. 4-5. Color break-up occurs on fast moving frames, especially on the edge of a object, or as a fast eye movement because the RGB image is incomplete and then destroyed by the next frame. Color break-up causes viewers visual fatigue, dizziness and headaches for a long time. Ogata *et al*. [40] used different projectors on subjects viewing the same video, and a questionnaire to examine their subjective feelings, such as feelings of dizziness, dry eyes and so on. Each symptom was given five grades, with the higher grade being more serious. Fig. 4-6 shows the statistical result after experiments where different bars represent different projectors (2×-DLP means that the rotational speed is 60Hz x2, and so on). The vertical axis represents the subjects' different scores before and after the experiment. A high score means serious visual fatigue. It is obvious that LCD projectors cause fewer fatigue problems, and DLP projectors with higher rotational speeds make subjects feel less fatigued. The way to reduce this effect is by improving the color wheel's rotational speed, but coordinating the DMD and color wheel becomes increasingly difficult, and the electrical circuit design becomes much more complicated. Another way is dividing a color wheel into red, blue and green. As the color wheel rotates once, the red, blue and green circle twice, so the rotational speed is doubled. Although it is effective to decrease the color break-up, the projector's brightness decreases when light passes through more colors.

Figure 4-5: The phenomenon of color break-up.

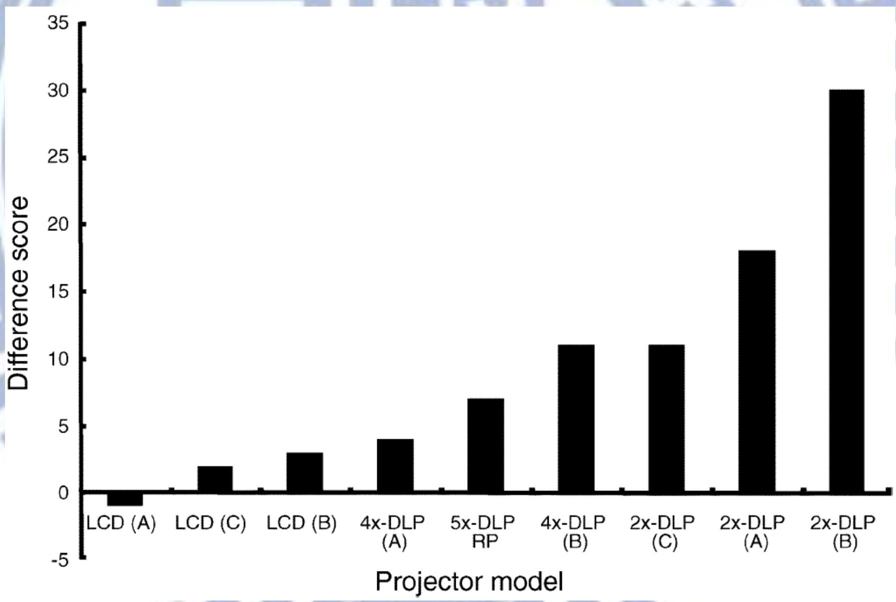

Figure 4-6: Different effects on visual fatigue by projectors [40].

4.1.2 Liquid Crystal Display

In 1968, the Radio Corporation of America developed a liquid crystal display that was lightweight and consumed little power. The most important aspect of the LCD is the materials which have properties of a conventional liquid and a birefringence of anisotropic crystals [80] that let light pass through a substrate by deflecting it into different angles for a display that is as effective as external electric fields. A polarizing filter is applied to the LCD. Imagine the light as a string wave with two mutually perpendicular vibrating directions. The two polarizing filters are fences that block the perpendicular direction of the string wave and bypass the parallel. It is the same way that the polarization of the passing light is selected through a polarizing filter. The liquid crystal layer becomes a way of changing the light's polarization through voltage control, as shown as Fig. 4-7. When the voltage is off, the layer's polarization changes, lets the light pass through, and the display is brightly lit. When the voltage is on, the liquid crystal molecules rotate and cannot change the light polarization, so the display is dark as the light is blocked. Thus, the combination of liquid crystal molecules changes to show gray levels as the external electric fields change with varying optical transmittance.

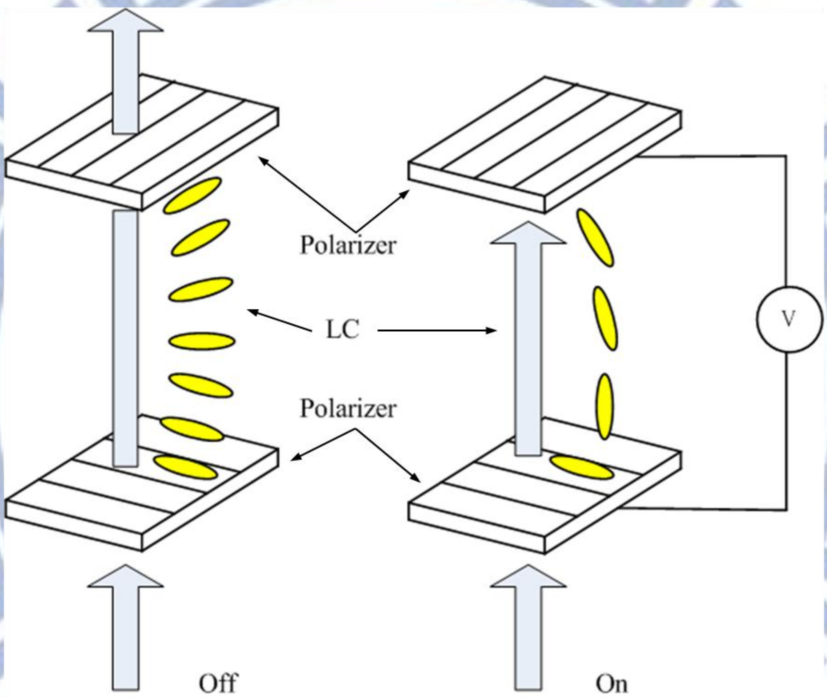

Figure 4-7: Different effects on visual fatigue by projectors.

The main reason that a LCD is able to show colored images is that red, green, and blue color filters are placed on a liquid crystal cell. The gray levels are formed by a back light passing through a liquid crystal layer control driver IC and through color filters to form red, green and blue and finally a color image for the eyes. Since liquid crystals do not emit light directly, the LCD is arrayed in front of a light source to produce colored images from different colored filters.

A color filter consists of a glass substrate, black matrixes, a color layer, an over coat and indium tin oxide (ITO), shown as Fig.4-8. The main function of the black matrix (BM) is to avoid a color mix effect between the colors. The purpose of the overcoat is to form a flat surface and keep the liquid crystal uncontaminated. ITO is used as a transparent conducting oxide with electrical conductivity and optical transparency, which is easily deposited as a thin film.

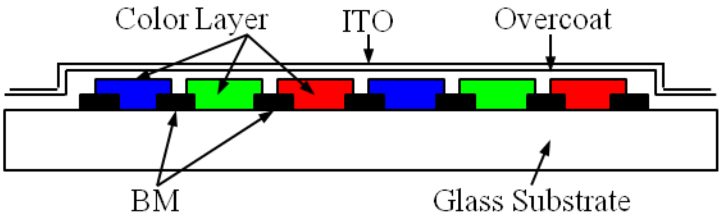

Figure 4-8: The structure of color filters.

In order to display images with good color quality, the arrangement of color filters is important. The color filters are fabricated by applying organic RGB materials to each pixel. Generally, the pixel arrangement is divided into stripes, mosaics, deltas, squares and so on, shown as Fig. 4-9. The RGB pixel is arranged individually into long stripes with three different neighboring colors, so thick stripes appear if the picture is larger, or if the figure is longitudinal. The mosaic places the RGB sideways to get more natural images than the stripe and a sharper oblique line for larger pictures. The RGB is arranged in a triangular shape in the delta and displays the most natural images, with a resolution 1.5 times the stripe but with the same number of pixels. It is often used in mid and small sized panels. The square feature occurs when a pixel consists of four points, like a square, instead of three, and is applied more to the image field. In summary, LCD TVs use liquid crystals to represent gray levels and use color filters to show colors.

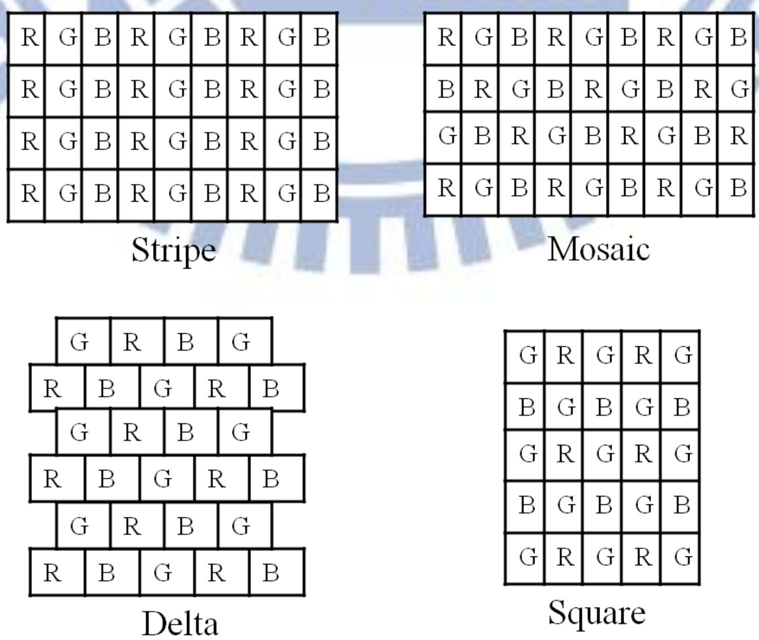

Figure 4-9: The geometrical combinations of color filters.

4.2 3D Display Technologies

3D Technology has been developing for over a century. Sir Charles Wheatstone (1833) drew the first stereo picture using a binocular parallax, and made a mirror stereoscope by mistake. Later on, Sir David Brewster (1818) made a prism stereoscope by using two lenses. Anderton (1891) introduced his findings that polarized light can be used to make 3D projectors. The 3D anaglyph became fashionable for a time in the 1950s, and even today there are still various 3D displays. From stereopictures to 3D, it is undeniable that 3D technology has continued to develop and progress.

As early as ancient Greece, people have noticed that although they possess two eyes, and the images received by the two retinas may not be the same, there are no double images. After several years of rigorous experimentation on animal and human bodies, it is evident that there are specific cells that are stereoscoptic [6, 7]. The human brain has the ability to merge two different images and generate depth perception. Stereoscopic vision is caused by binocular and motion parallaxes. Binocular parallax results from the eyes having different locations and visual angles, so their images are slightly different. Then the brain fuses the two into a stereo image. As the head moves, the vision angle changes causing a motion parallax. Using one of these two parallaxes can create a stereoscopic feeling. However, in order to achieve perfect stereoscopic vision, both of these parallaxes should be embedded, as moving the head affects 3D products. But, because viewers do not usually move a lot, binocular parallax is adopted in the present-day 3D displays.

3D displays can be divided into two types according to their appearances: stereoscopic and auto-stereoscopic [81], shown as Fig. 4-10. Stereoscopic displays can be classified as active and passive glasses, and other types. Active glasses mean shutter glasses in particular, whose purpose is to divide images into a right and left image, so that both eyes see different images. Adding in other factors such as persistence of vision, the viewed image is stereoscopic. The difference between the active and passive glasses is that their state is not altered, and does not require external power or synchronization with the screen. There is the theory that passive glasses are the same as active glasses. Both make the left eye see the left image, and the right eye, the right. Passive glasses can be divided into anaglyph and polarized glasses. The Red-Green and Red-Blue of the anaglyph are common. In this theory color images are processed for both the left and right eye. For example, the green image stays in the left eye while the red stays in the right; then the brain combines the two images so that they become a stereoscopic picture. As for viewers, the glasses send a slightly different image to each eye, but the brain fuses the images to make stereoscopic vision. There are two types of polarized glasses: linear and circular. The main principle is that it decomposes, distinguishes and preserves the image by the direction of the light waves. The 3D glasses have polarized glass with different directions for each eye. Thus a person's right and left eye can receive two images which will be combined into a stereo image. The head mounted display (HMD) is another type that puts two screens onto the glasses, and viewers can see a stereo image when the screens receive two different signals.

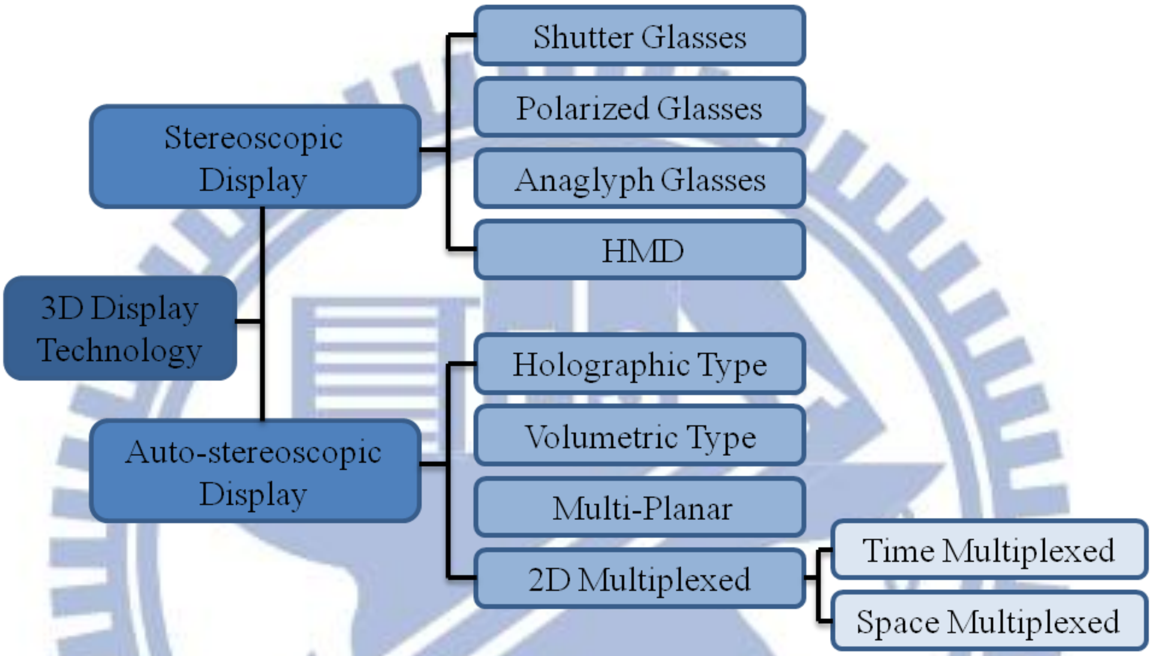

Figure 4-10: The sort of 3D display technology.

There are four types of auto-stereoscopic display: holographic, volumetric, multi-Planar and 2D multiplex. The holograph uses three laser light sources: red, blue and green, to generate phase grating through an acoustic optical modulator (AOM). The stereo image is created by amalgamating the laser with the hologram and scanning vertically with a vertical scanning mirror and horizontally with a polygonal mirror [82]. The Volumetric type uses a laser to scan stereo images. It uses a rapidly rotating vertical disk coordinated with a laser projector below the disk. When the laser light projects onto the revolving disk, it can scan every point in the space through a scatter effect to generate stereo images [83]. A Multi-Planar requires two liquid crystal displays. When these show images of the same size, the distance is varied between the viewers and objects so that there are differences in color and brightness. Once the images become superimposed, viewers can see the image in stereo. The 2D multiplex provides viewers with different 2D images angled from their right and left, in one system, but their brains combine these two images to generate stereo images. The 2D multiplex can be divided into space and time. Space divides the screen into right and left images and uses the parallax barrier or lenticular lens array to project into the right and left eye in order to create stereoscopic vision. The Parallax barrier [84, 85] a black and limpid longitudinal stripe, splits the light so that only the viewers' right eye receives the image projected by the LCD, and does the same with the left eye. But when the light goes through the black longitudinal stripe area, the brightness stays there because the light is absorbed. Therefore, the longitudinal stripes make up of two layers of chromium and aluminum replaces the black longitudinal stripes. When the light projects into the original black stripes, the aluminum layer reflects the light back to the stripes. The light is then recycled and the brightness improved. The lenticular lens projects left and right images into viewers' eyes irrespectively, and the brain sees the image stereoscopically. The time multiplex uses a special light splitting design to project continuous images into the viewers' left and right eyes at different times in order to display the image stereoscopically. When the left and right eye images are quick, the brain does not see the images change. The image angles for each eye are slightly different and so they become stereoscopic. One of the split light methods uses the parallax barrier serving the same purpose as the limpid and black longitudinal stripe, and then they switch places. That is, the longitudinal stripe becomes black and limpid. This exchange does not make one eye see just the same image, so it improves the resolution.

This highly developed 3D technology is used in present day stereoscopic displays, and the shutter and polarized glasses are excellent for these displays. Therefore, the present study utilizes these two 3D displays, which are introduced as follows.

4.2.1 Shutter Glasses

The basic concept of shutter glasses is the exchanging of left and right images in double frequency [86]. The glasses cover the users' left and right eyes. When the screen displays a left-eyed image, the glasses cover the right eye and vice versa. Therefore, both eyes see a different image. Although in this case, both eyes do not see the image simultaneously, due the persistence of vision, they do sense the image and have stereoscopic vision, shown as Fig. 4-11. When the screen displays a left-eyed image, the right glass becomes opaque and covers the right eye so only the left eye can see the image. The procedure is reversed for the right eye.

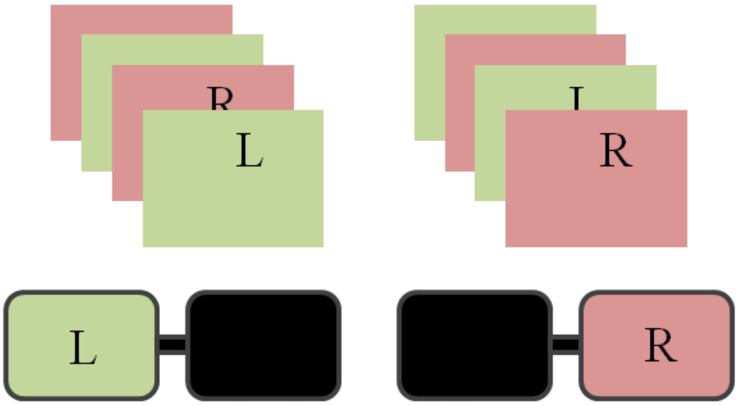

Figure 4-11: The theory of shutter glasses

Most of present day technology uses the LC, which is on the glass to control the transmitter in order to cover eyes. Aside from the glasses, the whole system also requires displays (projectors or screens) with a frequency double the norm. In general, traditional screens have a frequency of at least 60Hz in order to maintain good dynamic vision, while stereoscopic ones require over 120Hz because shutter glasses cover each eye in turn. Thus the quality of the stereoscopic vision would be good. Finally, the glasses and frame must synchronize perfectly, like using infrared rays to control the signal's transmitter. As a matter of fact, this technology did exist for a short period. However, the LCD frequency was not enough in its early days, as it failed to update frames at 120Hz. Therefore, coordinating with shutter glasses was unsuitable. However, thanks to recent technological breakthroughs the new LCDs can renew at 120Hz; some can even go as high as 240Hz; these are high enough to coordinate with shutter glasses.

4.2.2 Polarized Glass

The light waves move vertically in the transmitter's direction; they are unpolarized as the waves' uniform direction is polarized in a specific direction. The linear polarized glass allows light waves to pass in a specific direction through a special structure in order to achieve a polarizing effect. As Fig. 4-12 shows, in polarization, the green line and L are parallel light waves in the left eye's image, while the pink line and R are vertical light waves, and the image for the right eye. Then the vertical wave of light (the right eye's image) is blocked if only a parallel linear polarizer is set on the glasses' left eye to keep the left eye's image in line with the parallel wave, and the parallel light wave (the left eye's image) is the same. So far, the technology for individual eyes uses an interlaced polarizer. Half of the screen pixels display the left-side image and the others, the right, shown as Fig. 4-13. However, the polarizing system uses the polarizer's direction and angle to cover images for individual eyes. So the cross talk and double images may occur if the viewer's head is sideways and the direction and angle of the polarizer is not the same. Another design, the circular polarizer, has no angle problems, and places a quarter-wave retarder on the side of the linear polarizer. These wave plates are directional and generally, at a 45 degree angle to the linear polarizer. According to the relative angle to the linear polarizer (one is positive and the other is negative), circular polarizers are divided into left or right-handed polarized lights, shown as Fig. 4-14.

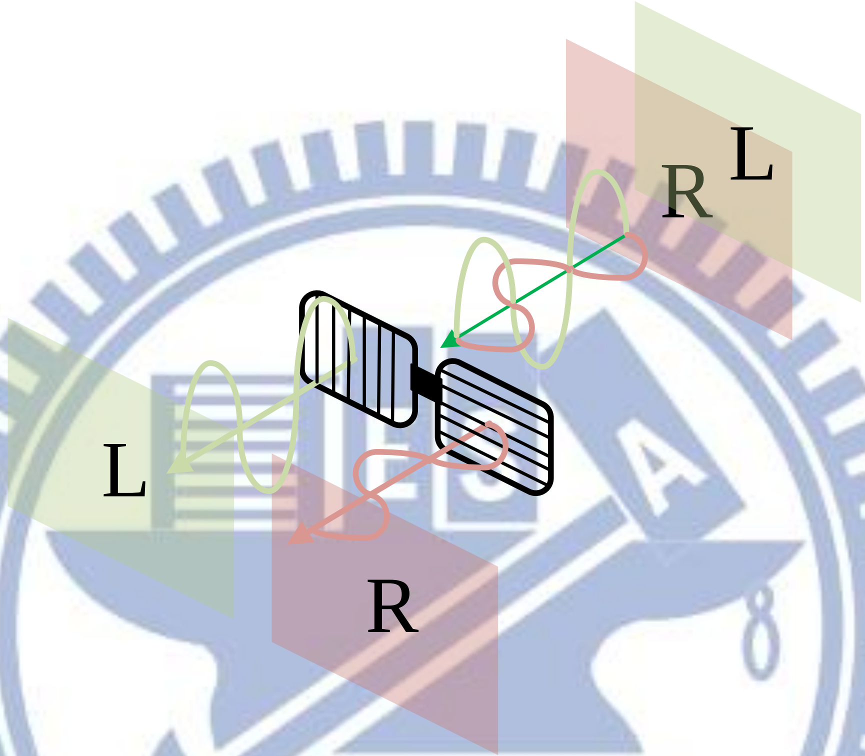

Figure 4-12: The theory of linear polarized system.

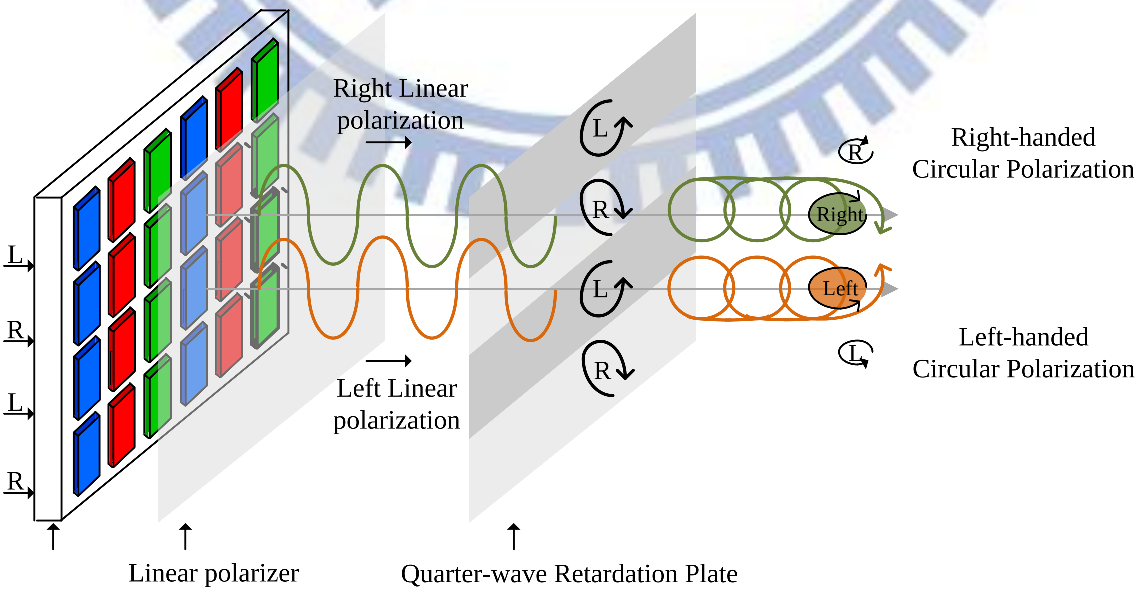

Figure 4-13: The theory of circular polarized system.

4.3 Light Sources

In general, displays are grouped into self-illuminating, Plasma, and external illumination, such as the LCD which is mostly set in the back. The uniform planar light source is selected because it does not damage the color display. Light sources (Electric light) are grouped into three types [87]: thermal radiation, gas-discharge and electroluminescence. Thermal radiation is a filament that is heated by a current to generate light and is used in incandescent bulbs and halogen lamps. Gas discharge lamps generate light by sending an electrical discharge through an ionized gas. They can be divided into low-intensity lamps such as low-pressure sodium and cold-cathode fluorescent lamps, and high-intensity lamps such as high-pressure mercury, sodium vapor and metal halide lamps. Electroluminescence generates light by sending electric current through solid materials such as light emitting diode (LED), OLED and laser diode (LD). This study used LED backlights as its light source for the two types of 3D LCD TVs and mixed LED and LD for the laser projector. LD and LED lights are detailed in the following sections.

4.3.1 Laser Diode

The first laser diode was introduced by Robert N. Hall in 1962 at the General Electric research center [88] and Marshall Nathan at the IBM T.J. Watson Research Center [89]. The laser diode generates light by stimulated emission, a population inversion and gains medium in a resonator [90], which has two common structures: homojunction and heterostruction. The heterostruction, together with the double heterojunction can restrict minority carriers in certain areas to increase gain and control of its refractive index so that the light is restricted to a luminous layer as a waveguide. The laser diode has a wide range of applications such as in communications, information systems (CD and DVD player) and precision measurements. Initially, the application was a single color TV made by Korpel *et al*.'s He-Ne laser in 1966. However, a full color TV needs three primary colors, and so far the high powered green laser appeared in the second harmonic generation [91] along with the GaN blue laser diode [92]. In addition to such general features as a single color, single directivity, focusing capabilities and interference, the laser diode is small, low in drive power and has a highly efficient photon-to-electron conversion and a high modulating rate.

4.3.2 Light Emitting Diode

The first Light Emitting Diode (LED) was invented in 1906 by Henry Joseph Round [93], but the first red LED was not invented until 1962. Later on, Shuji Nakamura from Nichia developed the blue LED [94] and proposed the phosphor by Yttrium Aluminium Garnet: Ce3+ (YAG:Ce3+) [95] which mixes with blue to generate white [96]. An LED generates light through a P-N junction using a P and N type semiconductor for converting electrons to photons. The LED wavelength that decides the energy level of the semiconductor's material depends on a mix of different materials. So far the InGaAlP is mainly red and yellow, and the InGaN is green and blue. The main LED applications are for illumination, communication and electronic consumer products, and in LED displays and backlighting. LED has highly efficient photon-to-electron conversion in low light and has such features as rapid response, long life, a focusing capability and either a single color or wider color range.

4.4 Comparisons of Three Aspects

Displays present visual information in either gray levels or full color (usually red, blue and green primary colors). A frame consists of many pixels that show color through color filters. In this study, two color formatting methods are referred to: time-sharing and spatial formation, which represent the DLP projector and LCD TV displays, respectively. The DLP projector system uses a color wheel that combines red, blue and green filters to produce full color. After the lights pass through the revolving color wheel, along with the different reflective times for the red, blue and green sections, they become a true color image in the human brain because of the persistence of vision threshold. Therefore, the color in a pixel is produced by discontinuous red, blue and green lights in a short time. In LCD TVs, every pixel can be divided into several sub-pixels with different geometrical combinations. Color information is not produced when the light source passes through the liquid layer. By using every color filter for each pixel, the correct color can be produced. Because the pixel density is larger than the human eye's resolution, color images can be produced. In summary, the human eye fails to identify the gaps between colors with spatial formation, or the interval time between colors with time-sharing.

Most 3D displays adopt the parallax method to produce the stereoscopic effect. This study uses two displays that occupy a big share of the market [97] : shutter glasses and polarized glasses. Shutter glasses use active covers to divide images into right and left-eyed images so that the eyes watch different images individually. This information is projected into the eyes, which then become stereoscopic. The main reason for polarized glasses is to deconstruct an original image by lightwaves, and to differentiate and cover the left and right images. Then different polarizers are adopted; finally, both eyes receive two images and the brain combines them into stereoscopic vision. Compared to other glasses, the shutter glasses are relatively expensive. The polarized glasses are cheaper and durable; therefore, they are more suitable for situations that accommodate lots of viewers.

Because LEDs generate light through spontaneous emission and the LD by stimulated emission, the difference between them is the light output of their bandwidth. The LED’s bandwidth is about 10nm, which is over ten times larger than an LD. Thus, the LDs’ color range is theoretically bigger than LEDs’. Besides, the driving critical current and output power of the LD are bigger, and its emission time is shorter than an LED, from about one tenth to one twentieth.

The following chapters investigate the effects of different variables on visual fatigue.

Chapter 5 Experiments

5.1 Purpose

This research discusses the effects of visual fatigue caused by different color formation methods, 3D technologies and light sources. Viewing 3D and 2D videos on three different displays to stimulate the human eye is one way to find the fatigue levels caused by these factors.

5.2 Experimental Equipment

5.2.1 Displays and the Farnsworth-Munsell 100-Hue Test

In order to research the effects on the human eye by color formation methods, 3D technologies and light sources, three displays were used in the experiment: a shutter 3D LCD TV (spatial formation method) and a polarized 3D LCD TV (spatial formation method) with LED back lighting, and a laser projector (time sharing method) with a mix of LED and LD backlighting. Also, both of the 3D LCD TVs can employ the 2D mode. The resolution of the 3D LCD TVs is Full HD (1920x1080), and the laser projector is XGA (1024x768).

The Farnsworth-Munsell 100-Hue Test is a direct device used to examine chromatic discrimination, and is used by this research as a basis for grouping subjects according to their chromatic discrimination abilities.

5.2.1.1 The Perception of Color

Cone cells play an important role in recognizing color. The normal human eye has three types of cones which peak at green, red and blue colors, respectively. According to the opponent color process theory (Hering, 1878) [98, 99], signals sent by the optic nerves, after the cone responses, integrate three opponent colors R-G, Y-B and W-K, shown as Fig. 5-1. People see color as interpreted by their brain. If the retina is missing two or three kinds of cones, color blindness is the result; if the retina is missing one kind of cone, it results in protanope, deuteranope or tritanope. If only one type of cone is missing, it causes different levels of anomalous, such as protanomalous, deuteranomalous or tritanomalous. So, chromatic discrimination can be abnormal if the numbers of cone cells vary unusually. People's chromatic discrimination is not the same because they possess different numbers of cones which can be examined by the Farnsworth-Munsell 100-Hue Test. Different hues are numbered from 1 to 85. The first number is red, with color wheel variations of orange, yellow, green…to purplish red and returning to red, shown as Fig. 5-2. Each hue differs from its neighbor, which is normally quite easy for a person to discern, with the distances between the various hues equal on a uniform chromaticity scale diagram[100].

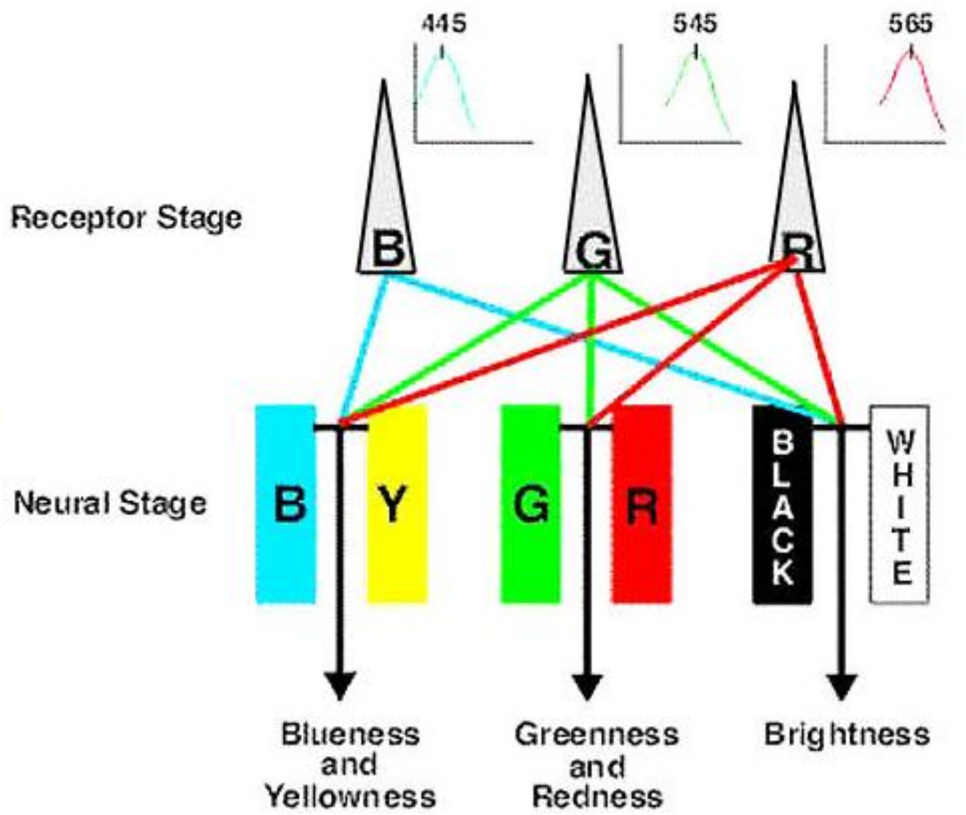

Figure 5-1: The model for normal human color vision. [101].

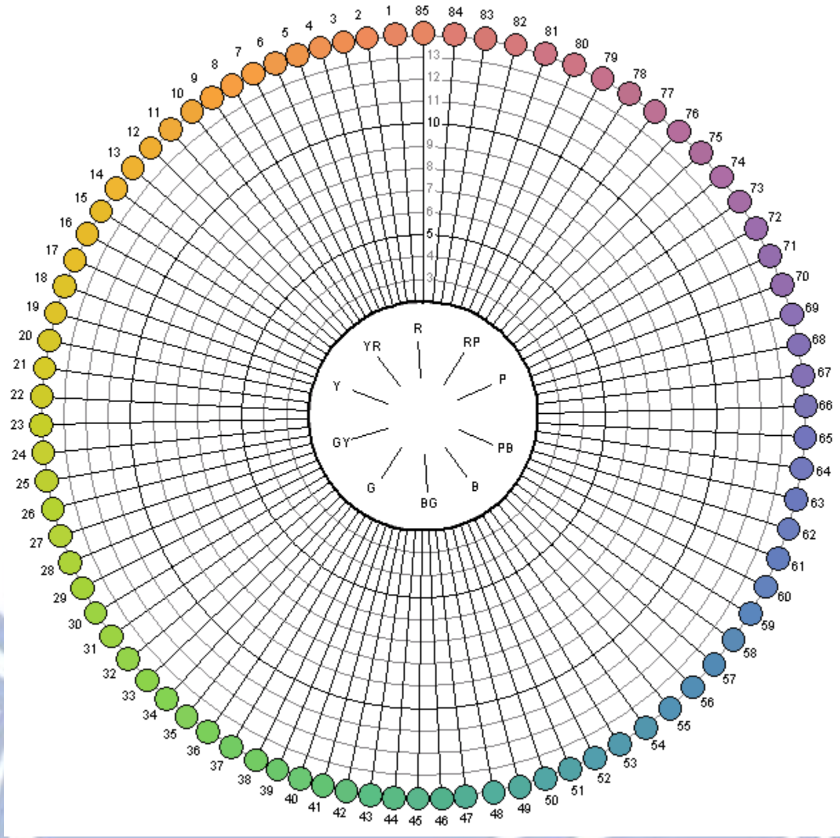

Figure 5-2: The hue plot of Farnsworth-Munsell 100-Hue Test.

5.2.1.2 Method for Evaluation of Chromatic Discrimination Power

The 85 colored caps are divided into four groups and put into four metal black boxes according to the color grading (first group: 85-21; second group: 22-42; third group: 43-63; fourth group: 64-84). Each box contains caps relevant to a part of the color spectrum plus two fixed reference color caps, one at each end, shown as Fig. 5-3. Before the experiment, an appropriate light source has to be chosen compatible with each cap's reflective spectrum. Thus, the spectrum for the light source has to be the same as the caps or have a higher color rendering. It is best to use a 6740°K standard illuminant C, or a 6500°K standard illuminant D65 with more than 269 lx (25 foot-candles) as a replacement[100, 102].

Figure 5-3: The colored caps.

The test requires each subject to pick one of the black boxes and sort the graded colors into a series of randomly arranged colored caps in a light box. The test time is 2 min for each box to prevent any effects due to the subject's hesitance. At the end of the test, the four boxes are closed and inverted individually by the examiner, and the numbers of each cap are inputted into the software for calculation. Each subject's test score is calculated as follows. Each cap number is compared to those of adjacent caps. If the arrangement is correct, the difference between the number of each cap and each of its neighbors is 1; thus a perfect score for each cap is 2. Take Fig. 5-4 for example: in box 1 the positions of caps 7 and 8 are incorrect; then the difference between caps 6 and 5 is 1 and that between caps 6 and 7 is 2, so the sum of differences for cap 6 is 2+1=3. The error score for each cap is defined as the difference between the abnormal and normal scores, so that cap 6 is 3-2=1. In this case, the actual error scores for caps 7, 8 and 9 are also 1, so the total error scores are 1+1+1+1=4, which is used to determine the subject's chromatic discrimination [100, 102, 103].

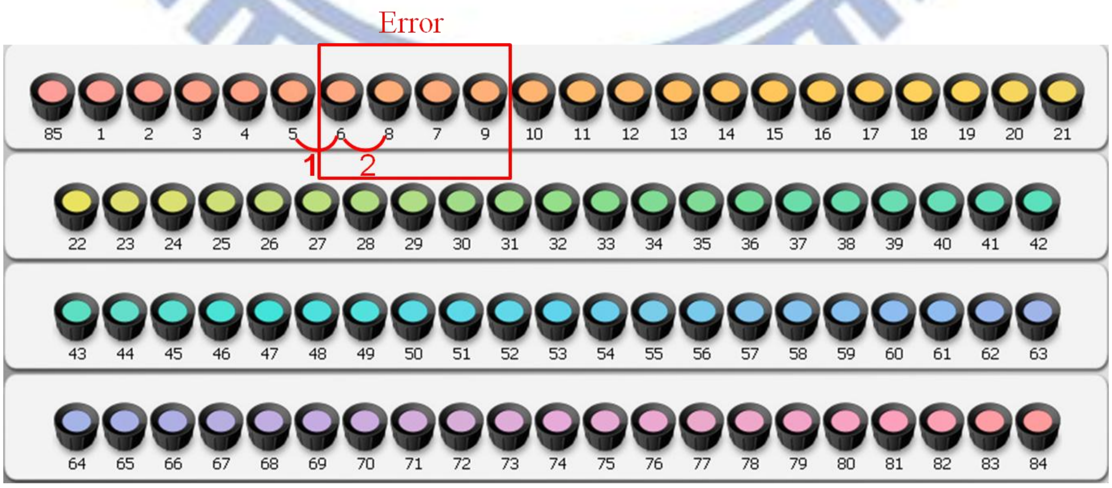

Figure 5-4: The error arrangement of caps.

In the standard reference, population 16% are superior (total error scores less than 20), 68% are average (total error scores between 20 and 100) and 16% are low (total error scores more than 100) [51].

5.2.2 Auto Refract-keratometer: Speedy-K Ver. MF-1

An auto refract-keratometer can record a subject's ciliary muscle microfluctuations through built-in targets. Subjects should gaze steadily at a target, which varies from +0.5D to -3.0D with 0.5D step, for a total of 8 targets. The target's stimulation time can be chosen when each mode is set. For this experiment, the "Screening Mode" is chosen and the measuring time is 1min, 40 sec. The reason that we would like to measure subjects in a shorter time is because the "Precise Mode" allows a measure time of 3 min 15 sec, which generally makes the subjects feel eyestrain, and their eyes ache. The measuring time for each target is 10 sec, and a maximum of 85 data are recorded, shown as Fig. 5-5.

The soft "MF-1" is then applied to analyzing the data, and calculations are made by the Fast Fourier Transform (FFT). The first step taken when calculating the HFC's spectral power is measuring subject's original accommodation power and excluding error data due to blinking or other reasons, and replacing it by using the cubic spline to a third degree interpolation, shown as Fig. 5-6. Then, the mean of wave is moved to zero, and the waveform was stilled. Third, a Hanning window is used as a filter due to the effect of terminal values during the FFT. Next, the first 9 sec of the data is divided into 6 slices, with values between 0 to 4 sec in the first slice, and values between 1 and 5 sec in the second slice, and so on, shown as Fig. 5-7. The six slices are transformed by the FFT. Finally, the mean spectral power is integrated into the frequency domain between 1 to 2.3Hz, and used to evaluate the research's visual fatigue level because it indicates ciliary body fluctuations. In total, there are six HFC data for each target.

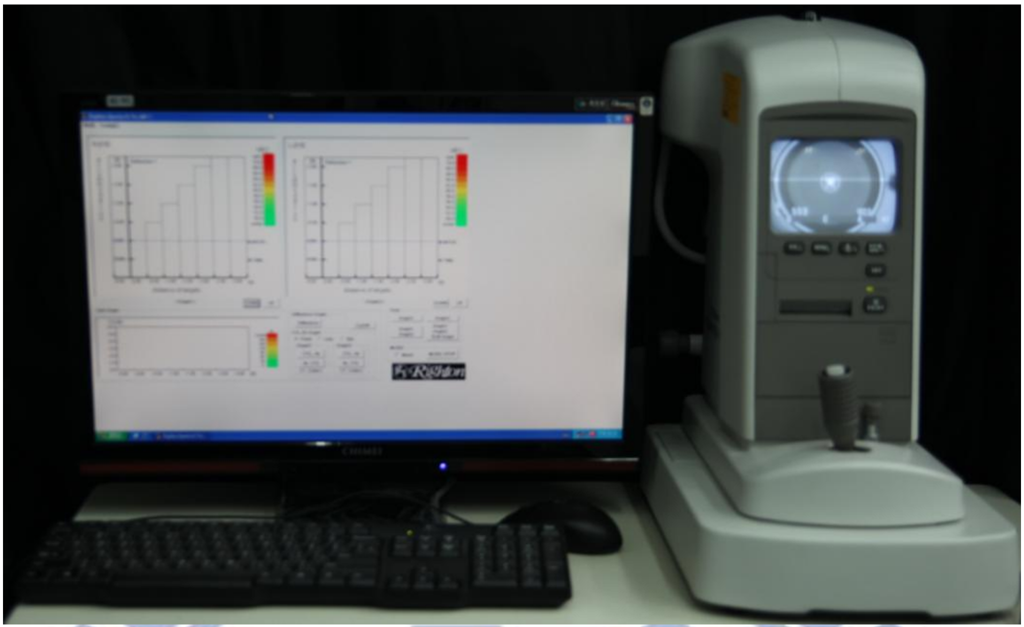

Figure 5-5: Auto Refract-keratometer: Speedy-K Ver. MF-1

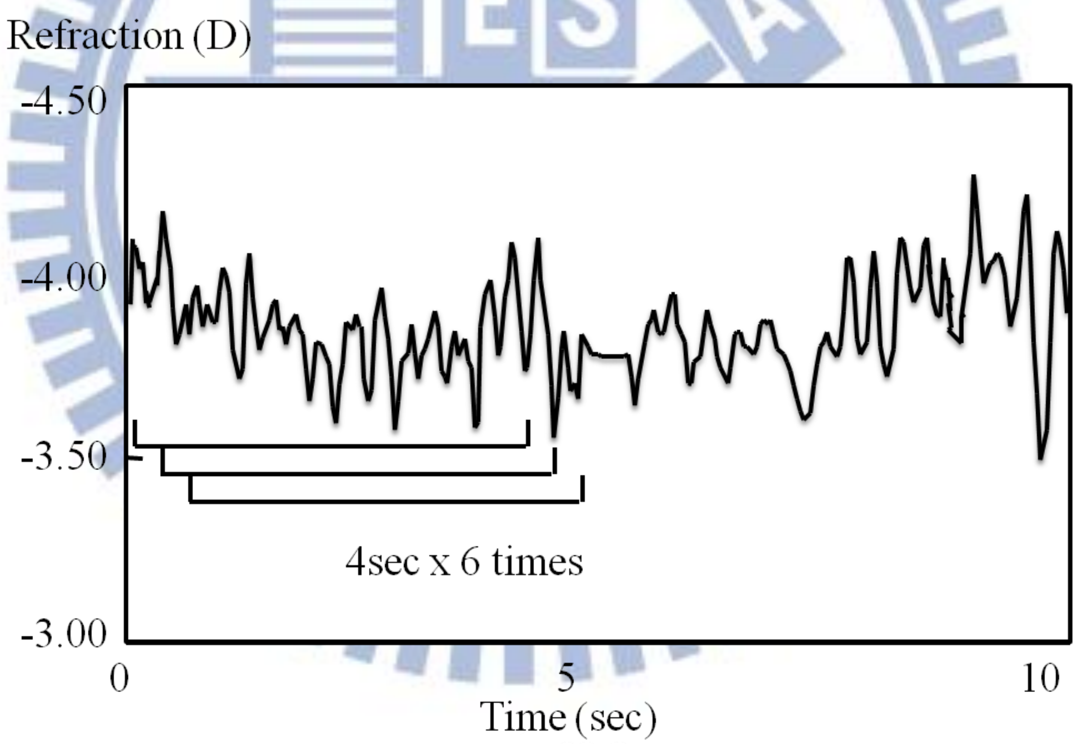

Figure 5-6: The accommodative microfluctuations of ciliary body.

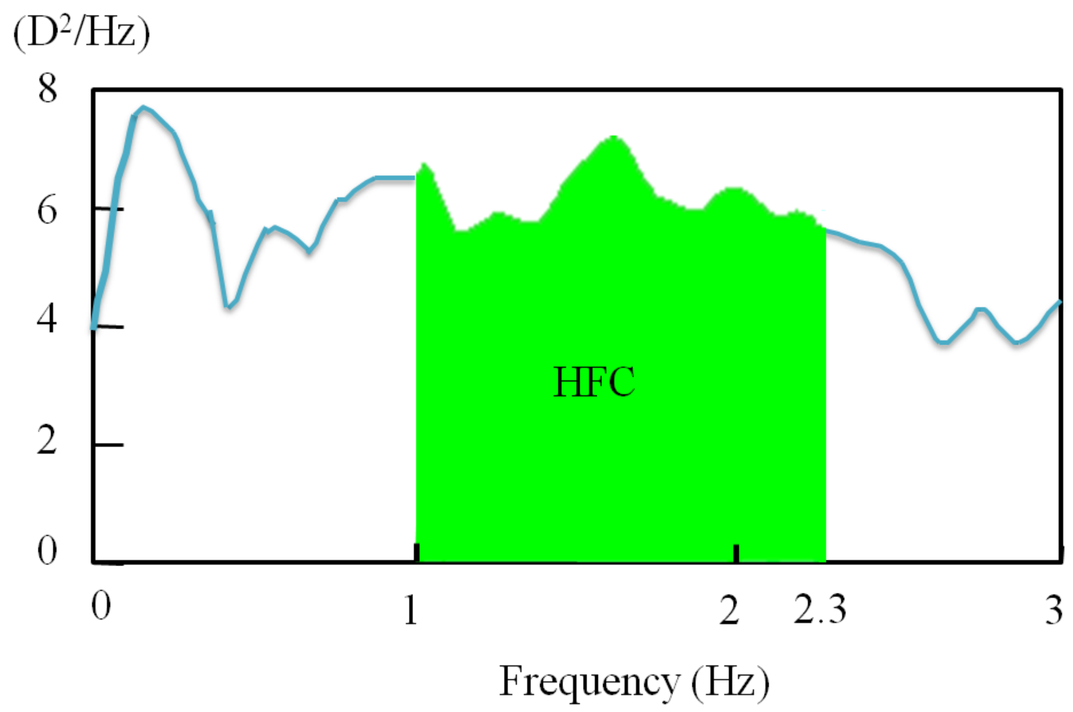

Figure 5-7: The calculation of spectra power of HFC.

5.3 Experimental Content

5.3.1 Experimental Design

There are stimulation sources in the experimental video. The two blue-ray DVDs: The Chronicles of Narnia: The Voyage of the Dawn Treader and The Green Hornet, were separated into 4 parts and randomly displayed on a shutter 3D LCD TV under 3D mode, a shutter 3D LCD TV under 2D mode, a polarized 3D LCD TV under 3D mode, a polarized 3D LCD TV in 2D mode and a laser projector. Each subject underwent a total of 20 times in the experiments.

The Questionnaire (Appendix 1) that is applied had symptoms with reference to Ogata (2005) [12]. The 15 symptoms evaluated in the experiment are: (1) eyestrain, (2) dry eyes, (3) too bright, (4) eyelid twitching, (5) feeling of pressure in the eyes, (6) ache behind the eyes, (7) blurred vision, (8) headache (9) head feels heavy, (10) head hurts when shaken (11) dazed feeling, (12) irritated feeling, (13) stiff shoulders, (14) sleepy feeling and (15) difficulty concentrating, shown as Table 5-1. The scores ranging from 1 to 5 are: (1) no symptoms, (2) mild, (3) fair, (4) strong and (5) severe. The total score is the sum of a single symptom score; thus, the maximum score is 75 (mean: 5) and the minimum score is 15 (mean: 1).

Table 5-1: The symptoms of visual fatigue.

No.	Symptoms	No.	Symptoms
1	eyestrain	9	head feels heavy
2	dry eyes	10	head hurts when shaken
3	too bright	11	dazed feeling
4	eyelid twitching	12	irritated feeling
5	feeling of pressure in the eyes	13	stiff shoulders
6	ache behind the eyes	14	Sleepy feeling
7	blurred vision	15	difficulty concentrating
8	headache		

5.3.2 Subjects

Ten subjects participated in the experiment, A, B, C, D, E, F, G, H, I and J, and their ages are: A(29), B(30) C(31), D(23), E(24), F(24) , G(26), H(31), I(24) and J(23).

A total of three hue tests are applied to each subject using the Farnsworth-Munsell 100-Hue Test, in the hope that it would lead to a discussion on the relationships among chromatic discrimination, color formation methods, 3D technologies and light sources. Finally, the subjects are divided into two groups: good chromatic discrimination (B, D, E, F and G) and normal chromatic discrimination (A, C, H and J), shown as Table 5-2. Before testing subjects were asked about such discomforts as eyestrain, headache or body stiffness, they then rest for 5 min to prevent any fatigue from affecting the test. The red label value is abnormal due to unfamiliarity with the hue test and is not adopted.

Table 5-2: The ages and color discrimination of 10 subjects.

Subject	Age	Score of Loss	Avg.	Chromatic Discrimination
A	29	104, 120, 108	110.7	Normal
B	30	8, 12, 4	8	Good
C	31	32, 32, 24	29.3	Normal
D	23	8, 16, 4	9.3	Good
E	24	24, 16, 8	16	Good
F	24	20, 8, 0	4	Good
G	26	56, 20, 28	24	Good
H	31	88, 88, 112	96	Normal
I	24	40, 16, 16	16	Good
J	23	36, 32, 36	34.6	Normal

5.3.3 Experimental Process

Fig. 5-8 is the flow chart for the experiment. The whole experiment is conducted in a dark room where the Farnsworth-Munsell 100-Hue Test is used to test the subjects' chromatic discrimination ability for discussing the relationships among chromatic discrimination, color formation methods, 3D display technologies and light sources. Ten subjects are picked to participate three times in the hue test under a D65 light source and then divided into two groups: good chromatic discrimination (total error scores less than 30) and normal chromatic discrimination (total error scores more than 30), with the number of subjects in each group being four and six. The displays used in the experiment are: a shutter 3D LCD TV, a polarized 3D LCD TV and a laser projector. The luminance for each display was 172.4, 234.9 and 250.7 cd/m^2 measured by a luminance meter (BM-7A), and the sizes of each screen were 40", 42" and 44", shown as Table 5-3. There were five modes in the experiment and each mode was tested four times. The first is the shutter 3D LCD TV under a 3D mode (S3D), the second is the shutter 3D LCD TV under 2D mode (S2D), the third is a polarized 3D LCD TV under 3D mode (P3D), the fourth is the polarized 3D LCD TV under 2D mode (P2D) and the last is a laser projector (LP), shown as Fig. 5-9. Before the experiment, subjects are asked to take a 5 min break to relax their eyes, and then the dipoters of the left eye are measured by the auto refract-keratometer in 1 min, 45 sec to get the HFC data. Upon completing the questionnaire on 15 symptoms (using a 5 point scale), subjects view the video sitting on the chair at about a 2 m distance from the screen for 15 min. The eye measurements aretaken again, and the questionnaire is filled in immediately afterwards. In order to prevent such a large number of subjects suffering from an accumulation of tiredness, each person is tested in only one mode a day. Finally, after all the data are collated and analyzed, the HFC is used as the major indicator. The questionnaire is used as a reference indicator for the analysis and discussion.

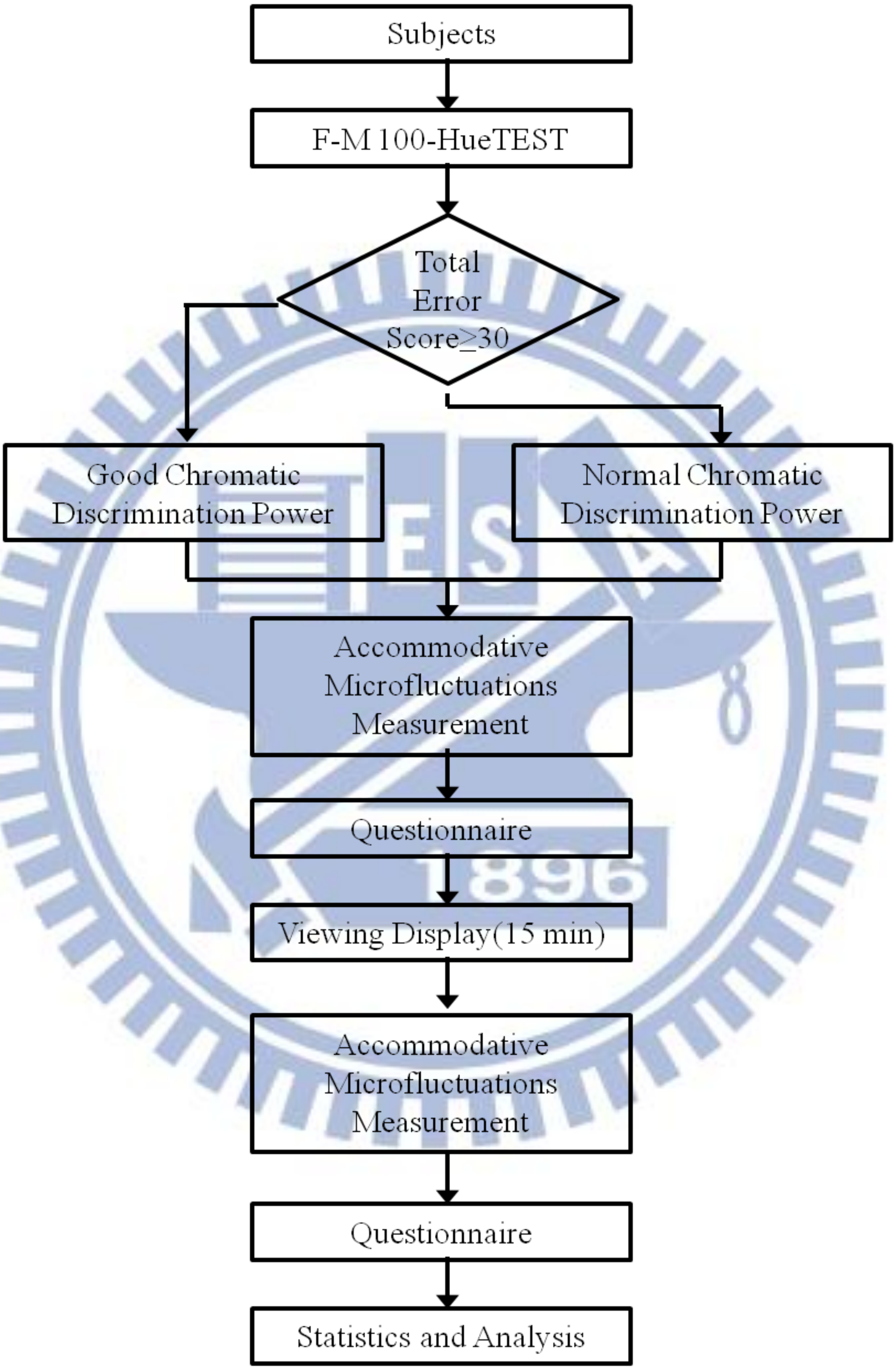

Figure 5-8: The flow chart of experimental process.

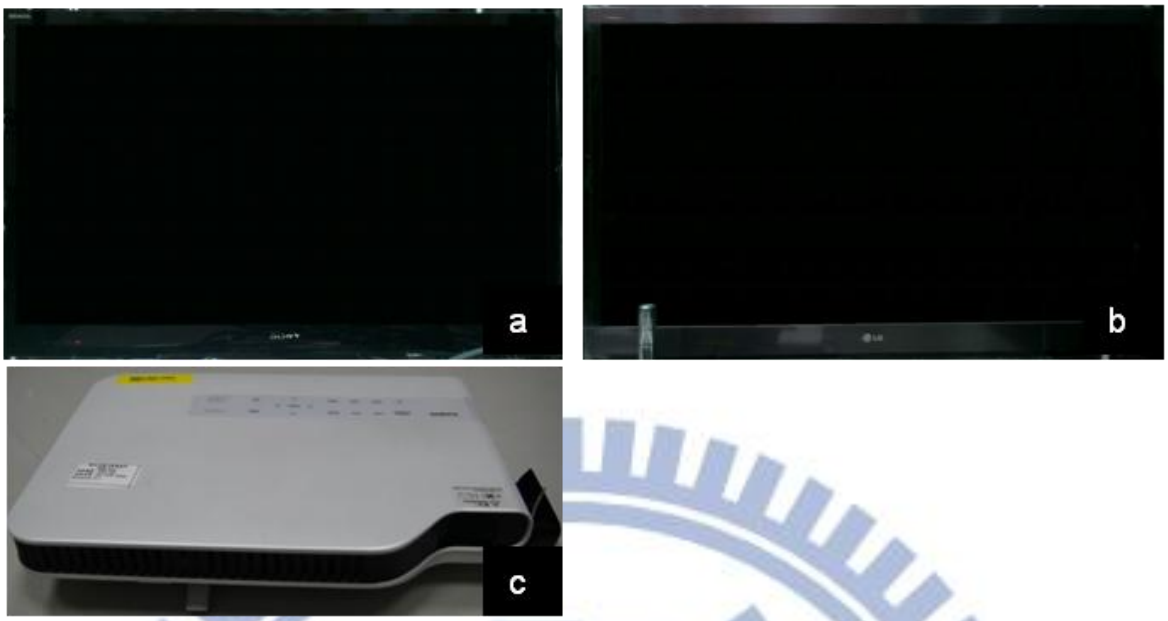

Figure 5-9: Three displays are (a) shutter 3D LCD TV (b) polarized 3D LCD TV (c) laser projector

Table 5-3: The displays and modes used in experiment.

Display and Mode Type	Notation	Luminance (cd/m^2)	Screen Size
Shutter 3D LCD TV under 3D mode	S3D	172.4	40
Shutter 3D LCD TV under 2D mode	S2D	172.4	40
Polarized 3D LCD TV under 3D mode	P3D	234.9	42
Polarized 3D LCD TV under 3D mode	P2D	234.9	42
Laser Projector	LP	250.7	44

Chapter 6 Results and Analysis

6.1 Results

Tables 6-1 and 6-2 show the mean △HFCs of 10 subjects in the 5 modes. In the tables, the mean △HFC for each subject is almost greater than 0; that indicates that the HFC can be use to evaluate visual fatigue during the 15 min viewing experiment. ANOVA is applied to test the validity of the experiment, and a one-tailed t-test was applied to compare the difference between each variable and to test its significance.

Tables 6-3 to 6-12 show the scores for the 10 subjects in the subjective questionnaire used to evaluate their visual fatigue in each mode. The calculation of each score is the mean of 4 experiments. The value greater than 0 means that subjects have visual fatigue after viewing the videos, while a value less than 0 means that the subjects have no visual fatigue after the test. To discover the different effects, a two-paired comparison was applied to each variable.

In addition to analyses of each variable, after the subjects are divided into 2 groups by the hue test, analyses of chromatic discrimination in each mode were conducted to understand how it affects visual fatigue. Without grouping, visual fatigue cases can only be observed with little consideration given to individual differences (chromatic discrimination power).

Table 6-1: The mean △HFCs of 5 subjects A to E under 5 modes.

Mode	Subject				
	A	B	C	D	E
S3D	1.511	-0.131	0.652	1.271	1.989
S2D	2.330	0.728	0.481	-0.222	0.547
P3D	2.950	1.092	0.812	-0.260	1.006
P2D	1.704	-0.163	0.392	0.167	0.873
LP	1.613	0.235	0.699	0.353	0.881

Table 6-2: The mean △HFCs of 5 subjects F to J under 5 modes.

Mode	Subject				
	F	G	H	I	J
S3D	1.350	1.757	1.401	0.640	3.887
S2D	0.340	0.300	0.165	0.524	1.065
P3D	0.202	0.783	0.950	1.073	0.122
P2D	-0.117	0.676	0.357	0.724	0.575
LP	0.968	1.381	1.904	0.345	1.932

Table 6-3: The scores of the subject A by subjective questionnaire under each mode

No.	Mode					No.	Mode				
	S3D	S2D	P3D	P2D	LP		S3D	S2D	P3D	P2D	LP
1	0.5	0.75	0.5	0.75	0.75	9	0.25	0	-0.25	0	0
2	0.5	0	0	0.25	0.5	10	0.25	0	0	0	0
3	1	0.5	0.25	0.25	0.25	11	0.25	0	0	0	0
4	-0.25	0.25	0.5	0	0	12	0	0	0	0	0
5	0.25	0	0	0	0	13	0	0.5	0	0	0
6	0	0	0	0	0	14	0.5	0.5	0.25	0.25	0.5
7	0.75	-0.25	0.25	0	0	15	0.75	0	0.25	0.25	0
8	0	0	0	0	0						
Sum	4.75	2.25	1.75	1.75	2						

Table 6-4: The scores of the subject B by subjective questionnaire under each mode

No.	Mode					No.	Mode				
	S3D	S2D	P3D	P2D	LP		S3D	S2D	P3D	P2D	LP
1	0.75	0.75	1	1	0.75	9	0.25	0.75	0.25	0.25	0.25
2	0.25	0.5	1	0.5	0.25	10	0	0.5	0	0.25	0.25
3	0.5	0	0	0	0.5	11	0.5	0.25	0.25	0	0
4	0	0	0	0	0	12	0.25	0	0	0.25	0.25
5	0.25	0.5	0.25	0.25	0.25	13	0	0	0	0	0
6	0.75	0	0.25	0.75	0.75	14	0	0.25	0	0.25	0
7	0.75	0	0.25	0	0.75	15	0	0	0.25	0.25	0.25
8	0	0.5	0	0.25	0						
Sum	4.25	4	3.5	4	2.75						

Table 6-5: The scores of the subject C by subjective questionnaire under each mode

No.	Mode					No.	Mode				
	S3D	S2D	P3D	P2D	LP		S3D	S2D	P3D	P2D	LP
1	1.25	0.5	0.5	0.5	1	9	0	0	0	0	0
2	0.25	0.5	0	0	0	10	0	0	0	0	0
3	0	0	0	0	0	11	0	0	0	0	0
4	0	0	0	0	0	12	0	0	0	0	0
5	-0.25	0	0	0	0	13	0	0	0	0	0
6	0	0	0	0	0	14	0	0	0	0	0
7	0	0	0	0	0	15	0	0	0	0	0
8	0	0	0	0	0						
Sum	1.25	1	1	0.5	1						

Table 6-6: The scores of the subject D by subjective questionnaire under each mode

No.	Mode					No.	Mode				
	S3D	S2D	P3D	P2D	LP		S3D	S2D	P3D	P2D	LP
1	0.5	0	0	0	0.25	9	0	0	0	0	0
2	0.5	0	0	0	0	10	0	0	0	0	0
3	0	0	0	0	0	11	0	0	0	0	0.25
4	0	0	0	0	0	12	0	0	0	0.75	0.25
5	0.75	0.25	0	0	0.25	13	0	0	0	0	0.25
6	0	0	0	0	0	14	0	-0.25	0	0	0.25
7	0	0	0	0	0	15	0	0	0	0.75	0.25
8	0	0	0	0	0						
Sum	1.75	0	0	1.5	1.75						

Table 6-7: The scores of the subject E by subjective questionnaire under each mode

No.	Mode					No.	Mode				
	S3D	S2D	P3D	P2D	LP		S3D	S2D	P3D	P2D	LP
1	0.25	0	0.75	0	0.75	9	0	0	0.25	0.5	0
2	0	0.25	0	0	0	10	0	0	0.25	0	0
3	0	0.5	0	0	0	11	0.5	0	1	0.25	0.25
4	0.5	0	0.25	0.25	0.75	12	1	0.75	0.25	0.5	0.75
5	0.75	0	0.25	0	0.25	13	0	0.25	0	0.5	0.5
6	0	0	0	0	0	14	0.75	0.5	0.25	0.75	1
7	0	0.5	0	0	0	15	0.5	0.75	0.5	0.5	0.5
8	0	0.25	0	0	0						
Sum	4.25	3.75	3.75	3.25	4.75						

Table 6-8: The scores of the subject F by subjective questionnaire under each mode

No.	Mode					No.	Mode				
	S3D	S2D	P3D	P2D	LP		S3D	S2D	P3D	P2D	LP
1	0.25	0.25	0.5	0.5	0.25	9	0	0	0	0.25	0
2	0.75	1	0.75	0.75	1.25	10	0	0	0	0	0
3	1	0.75	0.75	0.25	0	11	0	0	0	0.25	0
4	0	0	0	0	0	12	-0.25	-0.5	0.5	0	-0.25
5	0.25	0	-0.25	0	0	13	0	0	0	0	-0.25
6	-0.25	0	-0.25	0	0	14	0	0.25	0.25	0.75	0.25
7	0.5	0.5	0	0	0.75	15	-0.25	0	0	0.5	0.75
8	0.25	0.25	0	0	0						
Sum	2.25	2.5	2.25	3.25	2.75						

Table 6-9: The scores of the subject G by subjective questionnaire under each mode

No.	Mode					No.	Mode				
	S3D	S2D	P3D	P2D	LP		S3D	S2D	P3D	P2D	LP
1	0	0.5	0.75	0	0.5	9	0	0	0	0	0
2	0	1	0.5	0.5	0.5	10	0	0	0	0	0
3	0	0	0	0	0	11	0	0.25	0	0	0
4	0	0	-0.25	0	0	12	0	-0.25	0	0	0
5	0	0	0.75	0	0.25	13	0	-0.5	0	-0.25	0
6	0	0.5	-0.25	0.25	0	14	0.5	0.5	0.25	0	0
7	0.25	0.25	1	0.75	0.5	15	0.5	0.25	0.75	0.25	0
8	0	0	0	0	0						
Sum	1.25	2.5	3.5	1.5	1.75						

Table 6-10: The scores of the subject H by subjective questionnaire under each mode

No.	Mode					No.	Mode				
	S3D	S2D	P3D	P2D	LP		S3D	S2D	P3D	P2D	LP
1	1	1	0.75	0.75	0.75	9	0	0.25	0.25	0	0
2	1	0.5	1	1	0.5	10	0	0.25	0.25	0	0
3	0.75	0.75	1	1	0.75	11	0	0	0.25	0	0
4	0	0.25	0.5	0.25	0	12	0	0.25	0.25	0	0
5	0	0.25	0.5	0	0	13	0	0	0.25	0	0
6	0	0	0	0	0	14	0.5	0	0.25	0	0.25
7	0.5	0.75	1	0.25	0.5	15	0.5	-0.25	0.5	0	0
8	0	0	0	0.25	0						
Sum	4.25	4	6.75	3.5	2.75						

Table 6-11: The scores of the subject I by subjective questionnaire under each mode

No.	Mode					No.	Mode				
	S3D	S2D	P3D	P2D	LP		S3D	S2D	P3D	P2D	LP
1	0.25	0	0	0.25	0	9	-2	0	-0.25	0	0
2	0.5	0	0.5	0	0	10	0	0	0	0	0
3	0.25	0	0.25	0	0	11	0.5	0	0	0	0
4	0.25	0	0.25	0	0	12	0	-0.25	0	0	-0.25
5	0.25	0	0.25	0	0	13	0	0.25	0	0	-0.25
6	0	0	0	0	0	14	0	0.5	-0.25	-0.25	0.25
7	0	0.5	0.25	0	0	15	0.25	0	0.25	0.25	0
8	0	0	0.25	0	0						
Sum	0.25	1	1.5	0.25	-0.25						

Table 6-12: The scores of the subject J by subjective questionnaire under each mode

No.	Mode					No.	Mode				
	S3D	S2D	P3D	P2D	LP		S3D	S2D	P3D	P2D	LP
1	0.25	0	1	0.75	0.75	9	0	0.25	0	0.25	0
2	0.25	0.5	0.25	0.25	1	10	0	0	0	0	0
3	0.5	0	-0.25	0	0	11	0.5	0	0	0	0
4	0	0	0	0	0.5	12	-0.25	0	0	0	0.25
5	0.25	0.25	0	0.25	0	13	0	0	0	0	0
6	0	0	0	0	0	14	0	0	0	0	0
7	0	0.5	0.25	0	0	15	-0.25	0	0	0	0
8	0	0	0	0	0						
Sum	1.25	1.5	1.25	1.5	2.5						

6.2 Analysis Method

Due to the great number of individual differences in the human eye and the limited number of subjects and experiments, statistics are applied to the analysis and conclusion. First, the varied HFC (∆HFC) and the varied visual fatigue are calculated after viewing the video, minus the HFC prior to viewing the video. Each subject is tested 4 times in each mode, so each target resulted in 6 HFCs; thus, each subject has 6x8x4=192 data for each mode, and each subject already has192x5=960 data after viewing 5 modes.

All the data from this procedure are labeled with different variables, and the analysis of variance (ANOVA) and one-tailed t-test are used to find what effects the different color formation methods, 3D technologies and lighting sources have on visual fatigue. Different chromatic discrimination abilities are considered to determine the relationship between them and visual fatigue.

Besides, the ranking for mean scores is applied to analysis of questionnaires for finding what effects the different color formation methods, 3D technologies and lighting sources have on visual fatigue. Different chromatic discrimination abilities are considered to determine the relationship between them and visual fatigue, which is detailed in section 6.3.2.

6.3 Analysis

6.3.1 Analysis of the Objective Indicator (△HFC)

The ANOVA for two variables shows that the visual fatigue indicated by △HFC is dependent on the modes ($p<0.001$) and target distance ($p=0.001$) as well as the interaction between the modes and target distances, as shown in Table 6-13.

Table 6-13: The ANOVA for mode and distances of target.

Variables	SS	df	MS	F	P value
Mode (A)	1125.203	4	281.301	5.035	<0.001
Distance of target (B)	1139.696	7	199.957	3.579	0.001
AB	2846.310	28	101.654	1.820	0.005

Because the distance between the subjects and displays was about 2 m, a t-test for target distances above and below 2 m was done, and it shows that the △HFC mean is significantly greater in distances above 2 m (p<0.001), shown as Table 6-14. One explanation for this is that the lens curvature is smaller when eyes stare at far objects, and the ciliary body is relaxed. The lens curvature increases as eyes stare at close objects, and the ciliary body tenses. So, the △HFC will increase significantly as subjects are stimulated by far targets or suffering from visual fatigue or spasms. Otherwise, due to the ciliary body's tension, the △HFC will not increase as much; so it is better to adopt the data for the △HFC stimulated by far targets in the analyses [2,45]. According to the result of the above t-test, the full range of the △HFC used in the analysis is reasonable and effective.

Table 6-14: The t-test for distance of target above 2M and under 2M

Variables		N	Mean (SE)	P value
Distance of target	2M↑	3600	1.3 (0.124)	<0.001
	2M↓	6000	0.63 (0.097)	

Table 6-15 shows the t-test and compares the 5 modes. The results indicate that the △HFC by S3D is much larger than one by S2D (p<0.001) and the △HFC by P3D is much more than the one by P2D (p=0.035). Therefore, the subjects' ciliary body is tenser and more fatigued when viewing the 3D videos than the 2D videos. The subjects' △HFC is higher when viewing S3D than P3D (p=0.012), so the shutter system strains the subjects' ciliary body more than the polarized system does. There is no significant difference between viewing S2D and P2D (p=0.215), possibly because both of them are in the 2D mode using a spatial formation. Finally, the △HFC of watching LP is significantly different to S3D (p=0.052), S2D (p=0.045) and P2D (p=0.006), but not to P3D (p=0.257). The ciliary body tension is caused more by S3D than LP (p=0.045), but LP is more than S2D (p=0.045) and P2D (p=0.006). The latter result indicates that time sharing causes the human eye to experience more fatigue than the spatial formation method does.

Table 6-15: The t-test for each mode.

Variables (Mode)	N	Mean (SE)	P value
S3D	1920	1.43 (0.179)	<0.001
S2D	1920	0.63 (0.167)	
S3D	1920	1.43 (0.179)	0.012
P3D	1920	0.87 (0.172)	
P3D	1920	0.87 (0.172)	0.035
P2D	1920	0.44 (0.165)	
S2D	1920	0.63 (0.167)	0.215
P2D	1920	0.44 (0.165)	
S3D	1920	1.43 (0.179)	0.052
LP	1920	1.03 (0.171)	
P3D	1920	0.87 (0.172)	0.257
LP	1920	1.03 (0.171)	
S2D	1920	0.63 (0.167)	0.045
LP	1920	1.03 (0.171)	
P2D	1920	0.44 (0.165)	0.006
LP	1920	1.03 (0.171)	

Table 6-16 shows that the t-tests for the 3D and 2D modes, with the laser projector, also show that the 3D mode causes subjects to experience significantly higher levels of ciliary body tension (p=0.02). The 3D and 2D modes without the projector also show that the 3D mode causes much more serious tension (p<0.001). Thus, subjects strained the ciliary body more while viewing the 3D videos than the 2D videos. The t-tests for the DLP (laser projector) and LCD show that subjects have much more tension caused by the DLP (p=0.008), indicating that the time-sharing method causes more fatigue to the ciliary body than the spatial formation does. For the two kinds of 3D displays, subjects who viewed 3D videos with shutter glasses have significant ciliary body tension compared to those wearing polarized glasses (p=0.012).

Table 6-16: The t-test for 3D/2D(with LP), 3D/2D(without LP), DLP/LCD and shutter/polarized.

Variables (Mode)	N	Mean (SE)	P value
3D	5760	1.15 (0.124)	0.02
2D(with LP)	3840	0.7 (0.097)	
3D	3840	1.15 (0.124)	<0.001
2D(without LP)	3840	0.53 (0.118)	
DLP	1920	1.03 (0.171)	0.008
LCD(without 3D)	3840	0.53 (0.118)	
Shutter	1920	1.43 (0.179)	0.012
Polarized	3840	0.87 (0.172)	

Table 6-17 shows that the two kinds of light sources have no significant difference when compared to each other (p=0.162). It indicates that the LED backlight and LED mixed with LD have the same effect on fatigue and the ciliary body.

Table 6-17: The t-test for LED backlight and mixed LED and LD lights.

Variables		N	Mean (SE)	P value
Light Source	LED	7680	0.84 (0.085)	0.162
	LED+LD	1920	1.03 (0.171)	

Table 6-18 shows a detailed analysis of chromatic discrimination power. An interesting consistency, found in the results above, is that the subjects' △HFC with normal chromatic discrimination is higher than those with good chromatic discrimination power (p<0.001) under the 3D mode (p=0.005), 2D mode (p=0.04), the shutter system (p=0.024), the polarized system (p=0.055), LCD (0.039) and the laser projector (p=0.009). It is understood that individual differences affect the level of visual fatigue.

Table 6-18: The t-test for chromatic discrimination under each condition.

Variables (Chromatic Discrimination)		N	Mean (SE)	P value
All	good	5760	0.64 (0.097)	<0.001
	normal	3840	1.24 (0.124)	
3D	good	2688	0.87 (0.144)	0.005
	normal	1152	1.8 (0.240)	
2D	good	3456	0.56 (0.123)	0.040
	normal	2304	0.91 (0.157)	
Shutter	good	1152	1.15 (0.226)	0.024
	normal	768	1.86 (0.290)	
Polarized	good	1152	0.65 (0.219)	0.055
	normal	768	1.21 (0.276)	
LCD	good	2304	0.36 (0.151)	0.039
	normal	1536	0.79 (0.187)	
Laser Projector	good	1152	0.69 (0.213)	0.009
	normal	768	1.54 (0.285)	

6.3.2 Analysis of the Subjective Indicator (Questionnaire Method)

Fig. 6-1 shows the 10 subjects' questionnaire results. After 4 experiments, the mean difference score for each subject in each mode is calculated by taking the 15 scores for the symptoms after viewing the display minus the before scores and dividing them by 4. Because the individual subjective cognition is quite different, as shown in Fig. 6-1, it is hard to draw a conclusion or compare the different visual fatigue levels with each mode. Thus, the subjects' total score ranking for each symptom in each mode is applied to the following analyses on the relationship between individual differences and visual fatigue. In the figure, the red line labels the largest scores in each mode for S3D, P3D and LP at above four. A maximum point exists in P3D.

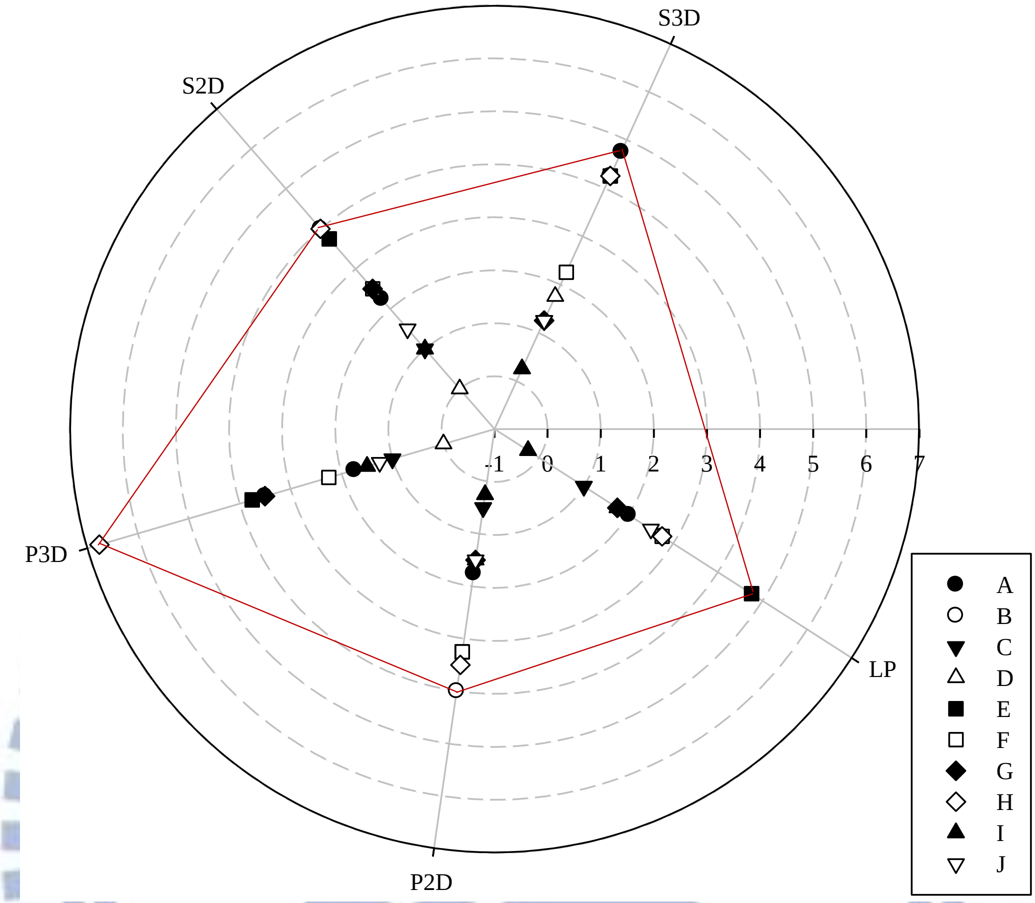

Figure 6-1: The result of the questionnaires from 10 subjects. The outer point means that discomfort level caused by the mode is more serious.

Fig. 6-2 shows the mean scores for symptoms from the ten subjects caused by each mode. The red line labels the highest scores for each symptom, (1) eyestrain, (2) dry eyes which are much more serious and common, (3) too bright, (5) feeling of pressure in the eyes, (7) blurred vision, (11) dazed feeling, (14) sleepy feeling and (15) difficulty concentrating, are also common symptoms. However, it is still hard to compare the effects of each variable. So the total ranking of mean scores for each symptom in the modes was used in the following analyzes of the relationship between each mode and visual fatigue.

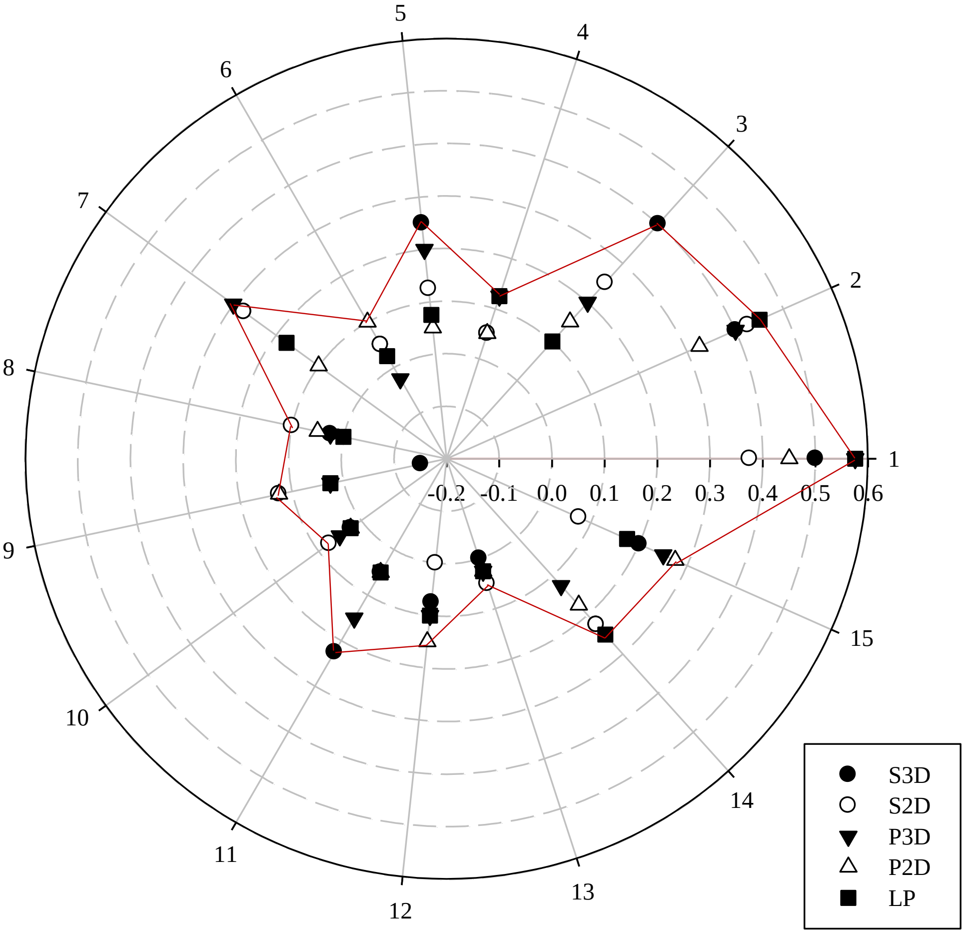

Figure 6-2: The scores of symptoms in each mode. The outer point means that discomfort level of the symptom is more serious. The symptoms of numbers are: (1) eyestrain, (2) dry eyes, (3) too bright, (4) eyelid twitching, (5) feeling of pressure in the eyes, (6) ache behind the eyes, (7) blurred vision, (8) headache (9) head feels heavy, (10) head hurts when shaken (11) dazed feeling, (12) irritated feeling, (13) stiff shoulders, (14) sleepy feeling and (15) difficulty concentrating.

The total ranking for mean scores of each symptom in the modes are ranked 5 (high) to 1 (low) for all 5 modes, and the total ranking for each mode is derived by summing up the 15 ranks, minus 15x2.5=37.5 (average), which was used to compare the effect on visual fatigue caused by different variables.

Fig. 6-3 shows the total ranking for each mode. The rankings for S3D and P3D are higher than the S2D, P2D and LP. Then S2D, LP and P2D are put in descending order from high to low. But there are no differences between S3D and P3D.

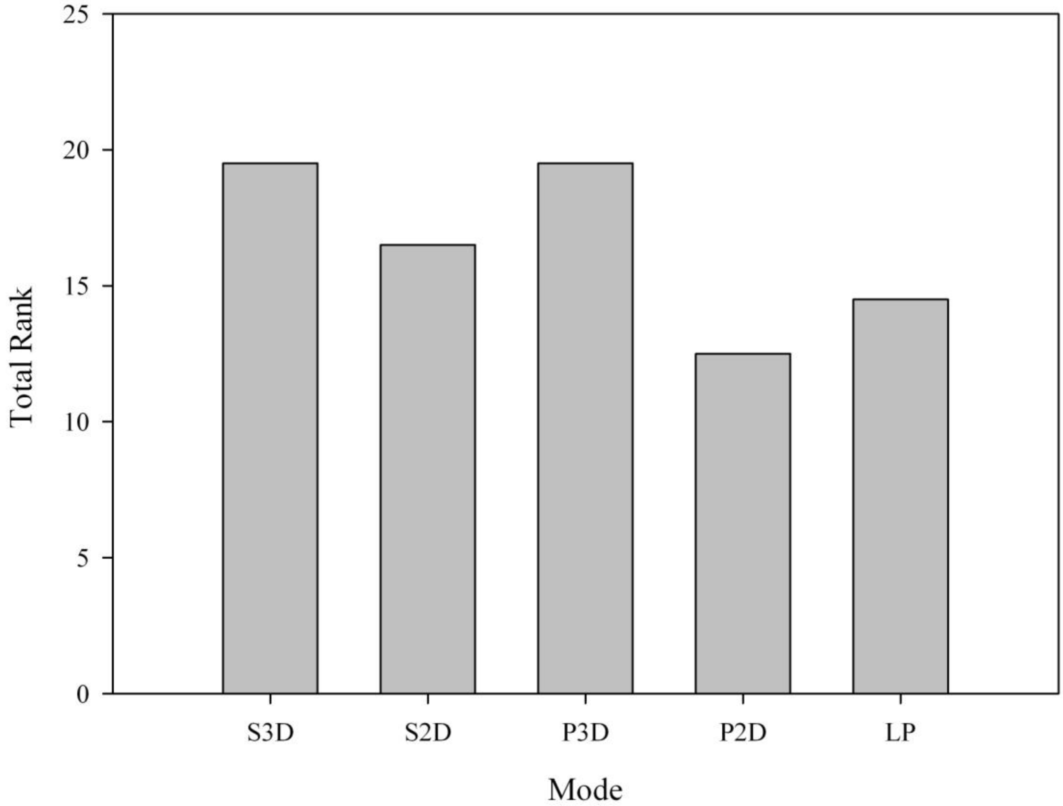

Figure 6-3: The total ranking for mean scores of each mode.

Fig. 6-4 shows the mean total rankings in the 3D and 2D modes, the LCD and DLP, and the shutter and polarized. The mean total rank in the 3D mode is higher than the 2D mode, but there are no differences between the LCD and DLP, or the shutter and polarized. It shows that 3D videos cause more visual fatigue than 2D ones do.

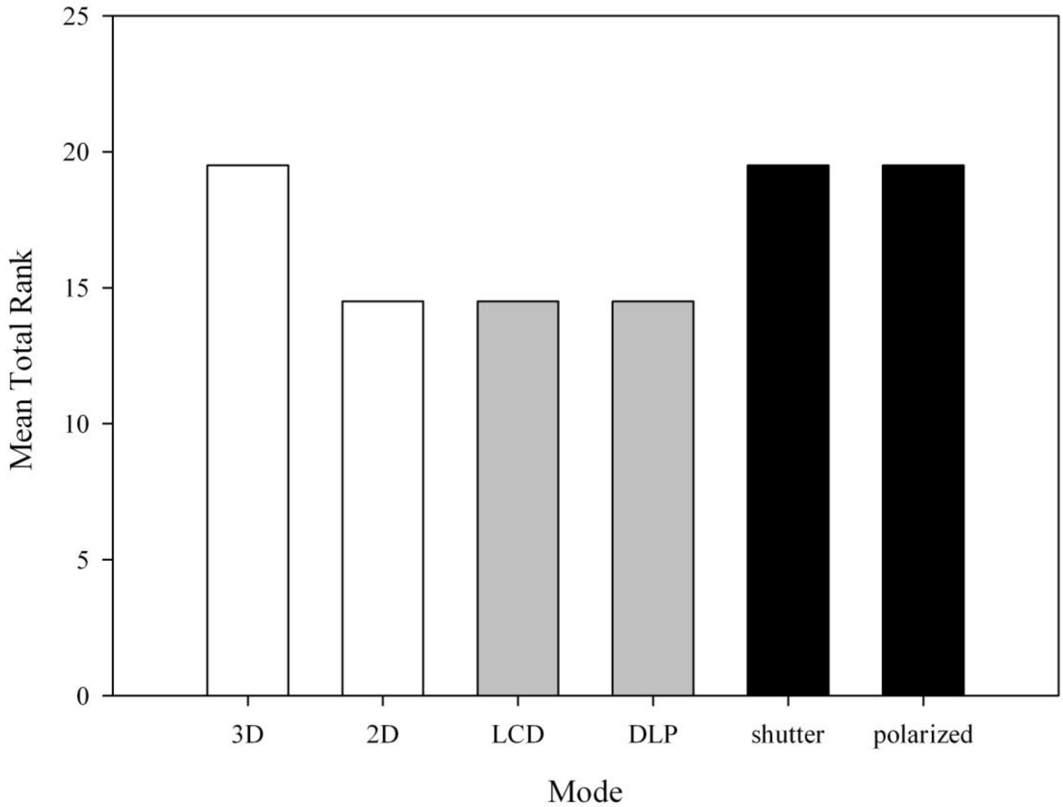

Figure 6-4: The mean total ranking for mean scores under 3D/2D mode (white), LCD/DLP (gray) and shutter/polarized (black).

To compare the relationship between individual differences and visual fatigue in each mode, the 10 subjects' total score for each symptom in each mode is ranked from 10 (high) to 1 (low), and each subject's total for each mode sums up the 15 ranks in each mode minus 15x5=75 (average).

Fig. 6-5 shows the mean total ranking for all subjects, and subjects under the 3D and 2D modes grouped by chromatic discrimination. The mean total ranking of subjects with normal chromatic discrimination and the ranking in the 3D mode are higher than those subjects with good chromatic discrimination. Subjects with good and normal chromatic discrimination power in the 2D mode are ranked almost the same. But there are no obvious results of comparison due to large standard errors.

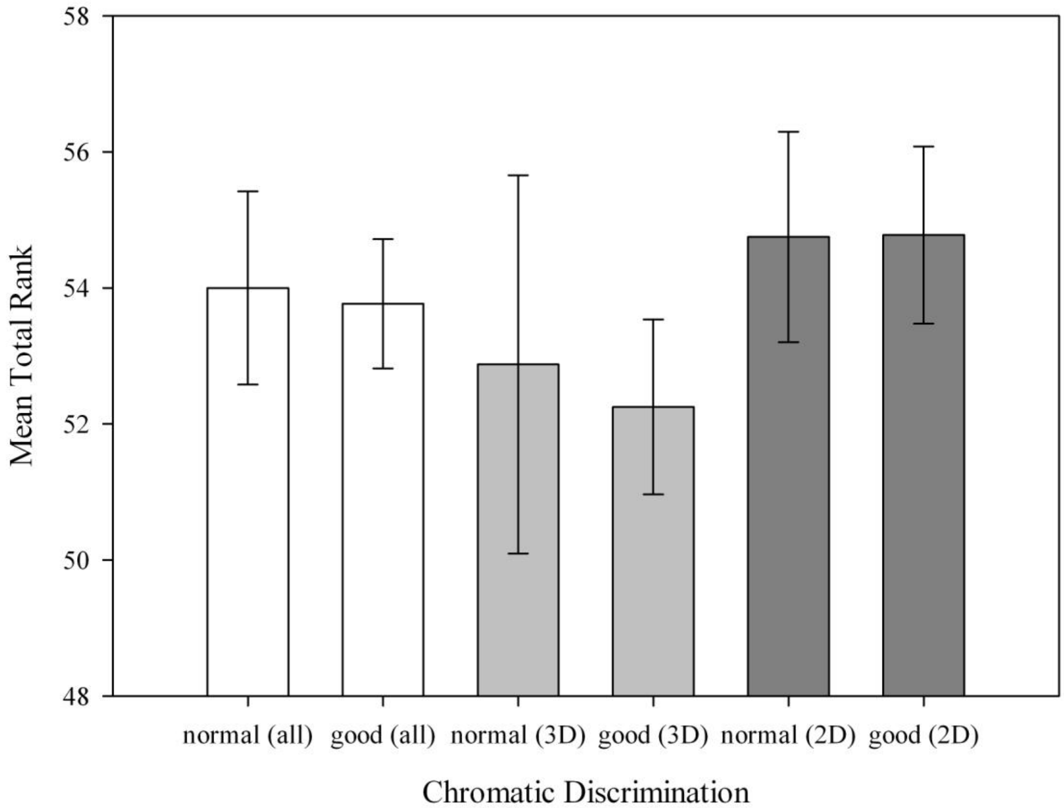

Figure 6-5: The mean total ranking for scores of all subjects (white), subjects under 3D mode (gray) and 2D mode (dark gray) grouped by chromatic discrimination.

Fig. 6-6 shows the subjects' mean total ranking under the shutter and polarized systems when grouped by chromatic discrimination. The ranking of subjects with normal chromatic discrimination under the shutter system is higher than those with good chromatic discrimination, but there is no obvious difference between subjects with either good or normal chromatic discrimination power when viewing 3D videos with polarized glasses. But there is also no obvious result of comparison due to large standard errors.

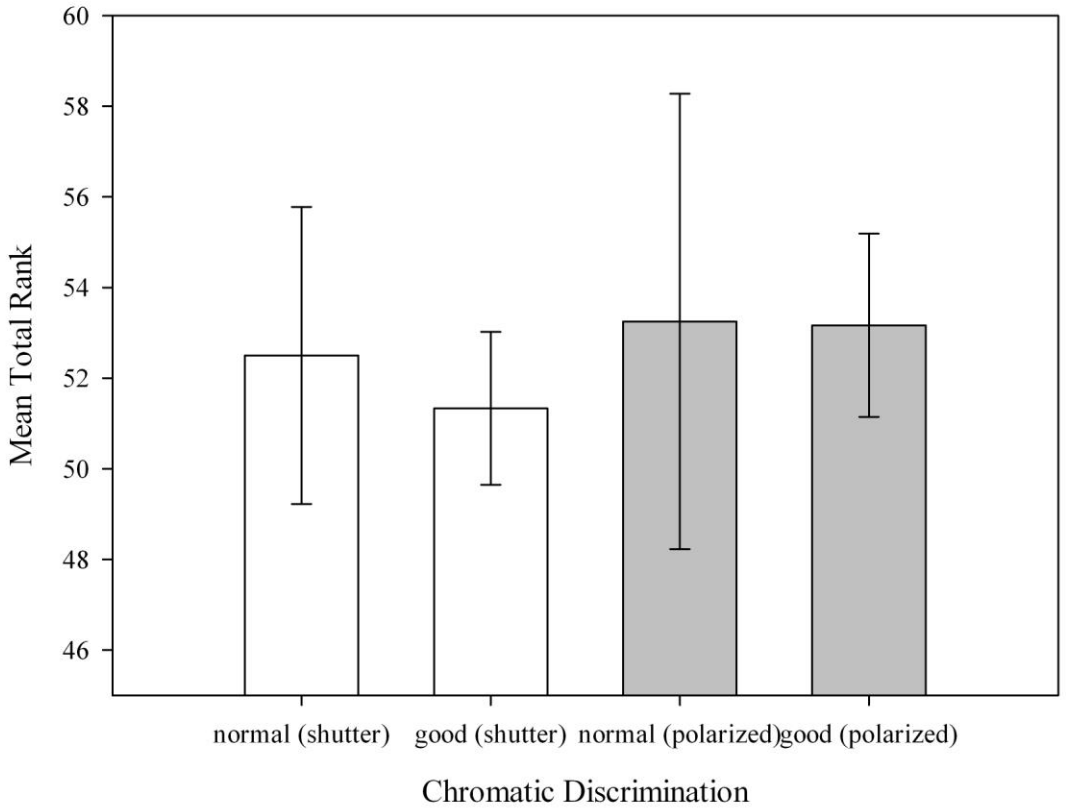

Figure 6-6: The mean total ranking for scores of subjects under shutter system (white) and polarized system (gray) grouped by chromatic discrimination.

Fig. 6-7 shows the mean total rankings for subjects in the LCD and DLP grouped by chromatic discrimination. The rankings of subjects with good chromatic discrimination under the DLP is higher than those with normal chromatic discrimination, while the opposite is true with the LCD where the ranking of subjects with good chromatic discrimination is lower than those with normal chromatic discrimination power. Due to large standard errors, there are no obvious results of comparison, too.

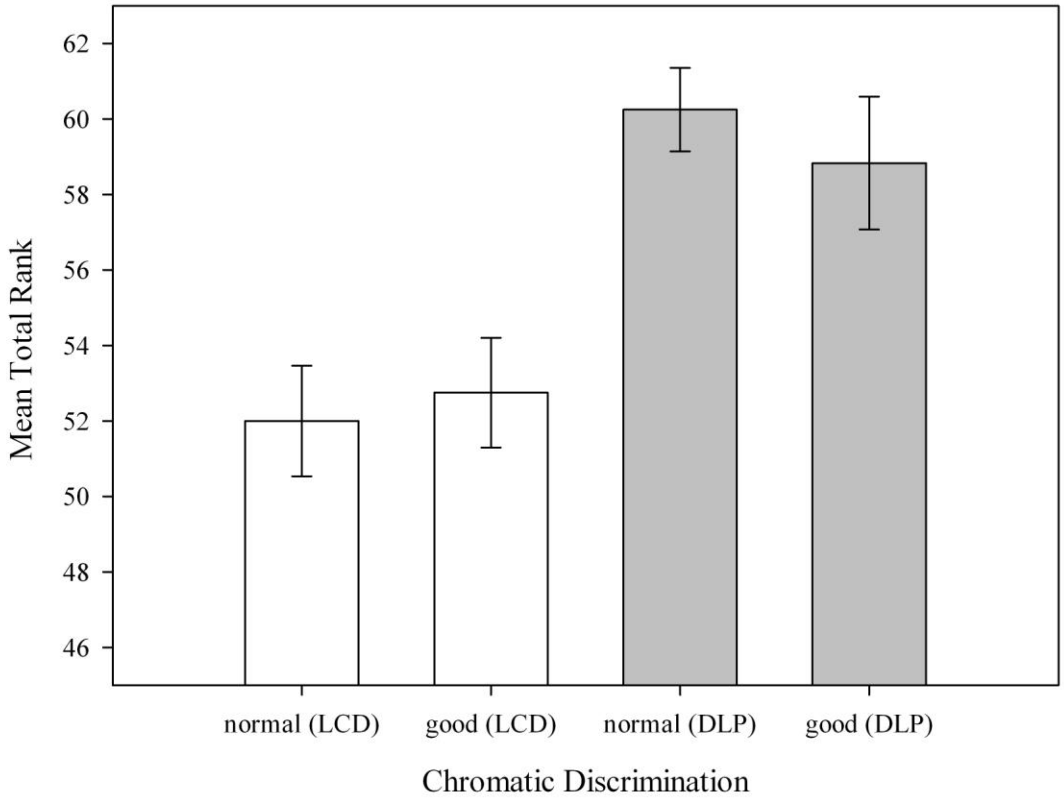

Figure 6-7: The mean total ranking for scores of subjects under LCD (white) and DLP (gray) grouped by chromatic discrimination power.

According above those results, it is hard to conclude that the effects of conditions on viewers grouped by chromatic discrimination because of large standard errors. So, changing analysis method might is needed to improve the effectiveness of the questionnaire.

It is noticed that among the 15 symptoms on the questionnaire only 8 are obvious: (1) eyestrain, (2) dry eyes are much more serious and common, (3) too bright, (5) feeling of pressure in the eyes, (7) blurred vision, (11) feeling dazed, (14) feeling sleepy and (15) difficulty concentrating. After evaluation by their mean scores compared to the total mean score, 6 major symptoms,(1) eyestrain, (2) dry eyes are much more serious and common, (3) too bright, (7) blurred vision, (14) feeling sleepy and (15) difficulty concentrating, are chosen to evaluate the effects on viewers by different variables, as shown as Fig. 6-8.

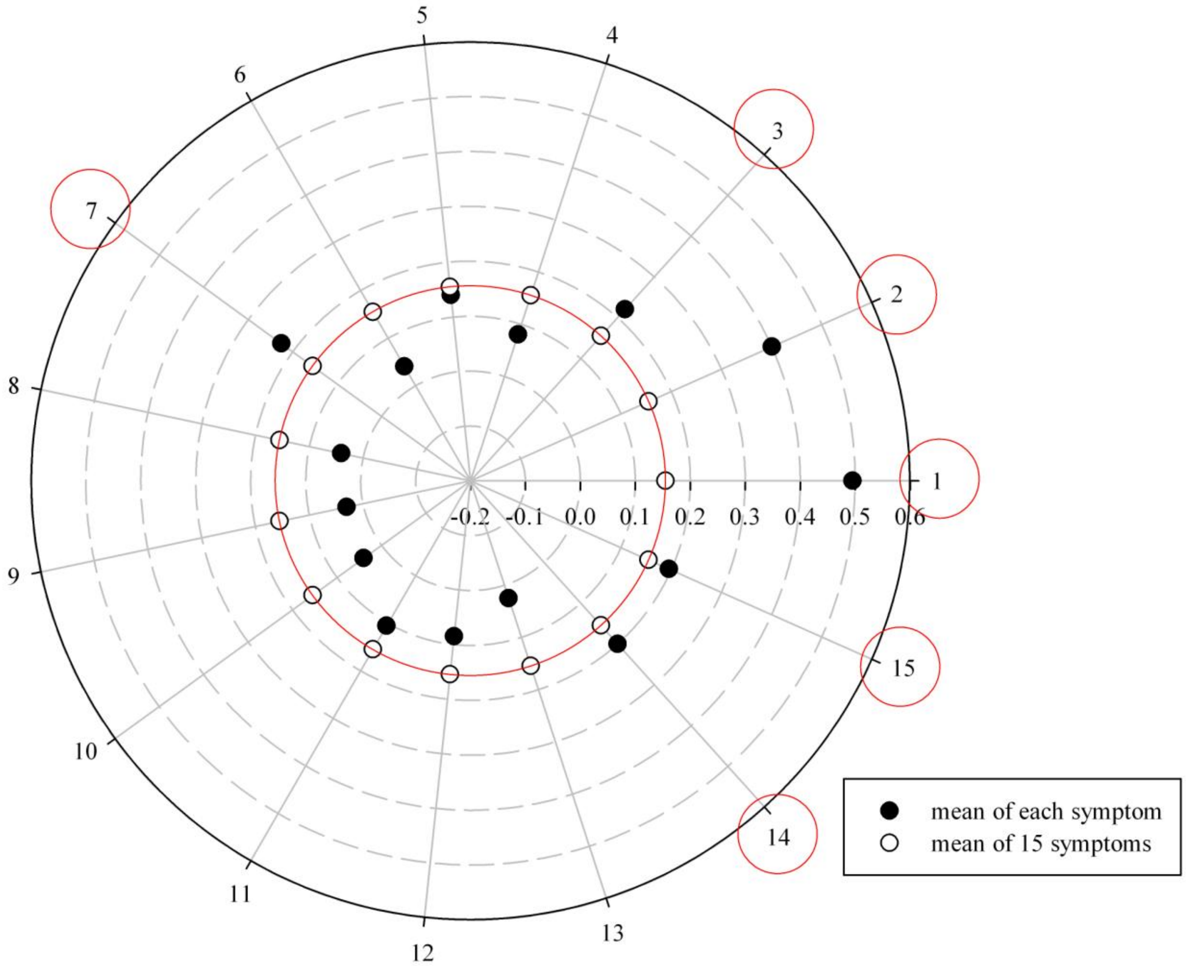

Figure 6-8: The comparison between the mean score of each symptom and the mean scores of 15 symptoms. The symptoms of numbers are: (1) eyestrain, (2) dry eyes, (3) too bright, (4) eyelid twitching, (5) feeling of pressure in the eyes, (6) ache behind the eyes, (7) blurred vision, (8) headache (9) head feels heavy, (10) head hurts when shaken (11) dazed feeling, (12) irritated feeling, (13) stiff shoulders, (14) sleepy feeling and (15) difficulty concentrating.

The total ranking for mean score of 6 major symptoms in the modes are ranked 5 (high) to 1 (low) for all 5 modes, and the total ranking for each mode is derived by summing up the 6 ranks, minus 6x2.5=15 (average), which was used to compare the effect on visual fatigue caused by different variables.

Fig. 6-9 shows the mean total rankings in the 3D and 2D modes, the LCD and DLP, and the shutter and polarized by 6 major symptoms. The mean total rank in the 3D mode is higher than the 2D mode, in the DLP is higher than LCD, and in the shutter is higher than polarized. It shows that 3D videos cause more visual fatigue than 2D ones do. The DLP systems cause more visual fatigue than LCD and the shutter cause more visual fatigue than the polarized does.

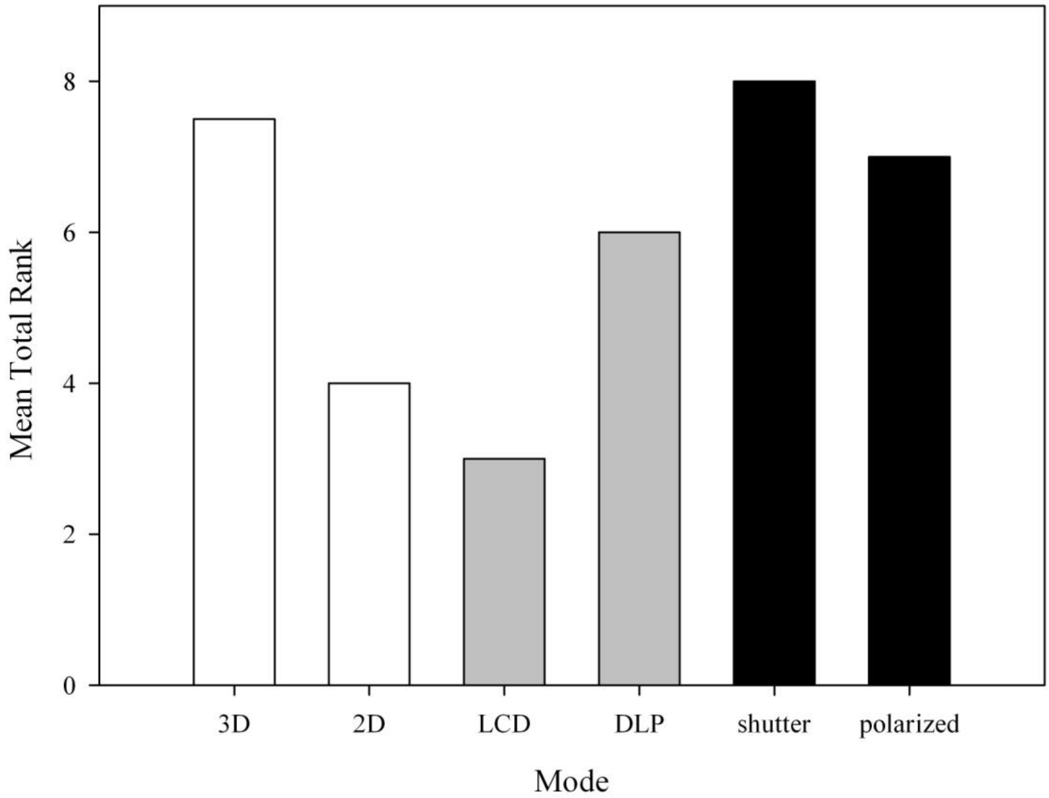

Figure 6-9: The mean total ranking for mean scores under 3D/2D mode (white), LCD/DLP (gray) and shutter/polarized (black) by 6 major symptoms.

To compare the relationship between individual differences and visual fatigue in each mode, the 10 subjects' total score for 6 major symptoms in each mode is ranked from 10 (high) to 1 (low), and each subject's total for each mode sums up the 6 ranks in each mode minus 6x5=30 (average).

Fig. 6-10 shows the mean total ranking by 6 major symptoms for all subjects, and subjects under the 3D and 2D modes grouped by chromatic discrimination. The mean total ranking of subjects with normal chromatic discrimination (p=0.13) and the ranking in the 3D (p=0.18) and 2D (p=0.27) mode are higher than those subjects with good chromatic discrimination. Thus, when viewing 3D and 2D videos, subjects with normal chromatic discrimination power generally suffer more visual fatigue than those with good chromatic discrimination.

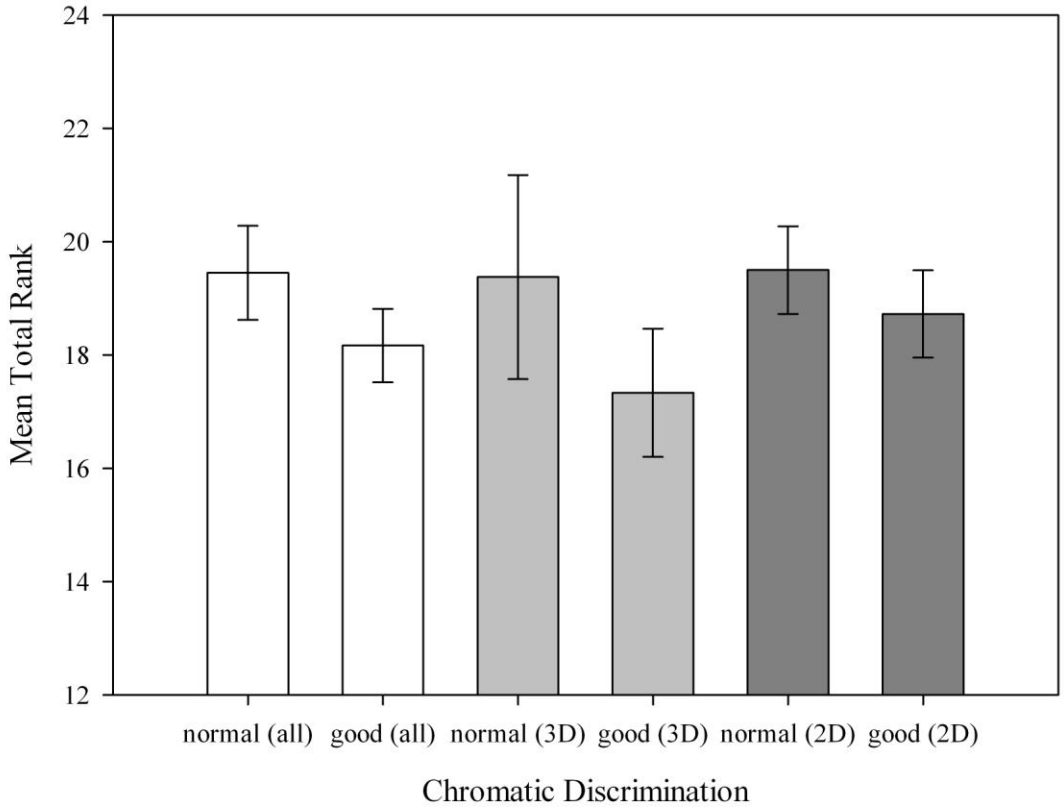

Figure 6-10: The mean total ranking for scores by 6 major symptoms of all subjects (white), subjects under 3D mode (gray) and 2D mode (dark gray) grouped by chromatic discrimination.

Fig. 6-11 shows the subjects' mean total ranking by 6 major symptoms under the shutter and polarized systems grouped by chromatic discrimination. The ranking of subjects with normal chromatic discrimination under the shutter system is higher than those with good chromatic discrimination (p=0.11), but there is no obvious difference between subjects with either good or normal chromatic discrimination when viewing 3D videos with polarized glasses (p=0.49).

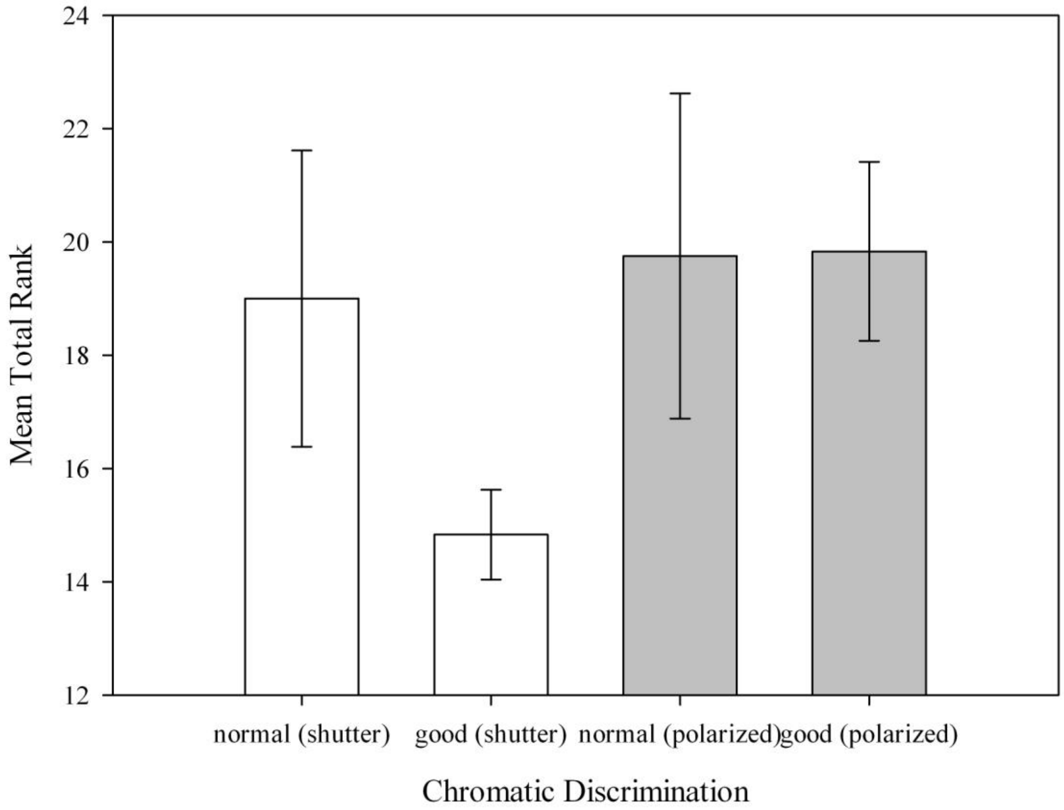

Figure 6-11: The mean total ranking for scores by 6 major symptoms of subjects under shutter system (white) and polarized system (gray) grouped by chromatic discrimination.

Fig. 6-12 shows the mean total rankings by 6 major symptoms for subjects in the LCD and DLP grouped by chromatic discrimination power. The rankings of subjects with good chromatic discrimination under the DLP is higher than those with normal chromatic discrimination (p=0.19), while there is no obvious different effect by the LCD on subjects with normal chromatic discrimination and those with good chromatic discrimination (p=0.43).

Thus, in general subjects with normal chromatic discrimination suffer more visual fatigue than those with good chromatic discrimination. Besides, subjects with normal chromatic discrimination suffer more from visual fatigue while viewing 3D videos with shutter glasses and viewing 2D videos on the DLP system.

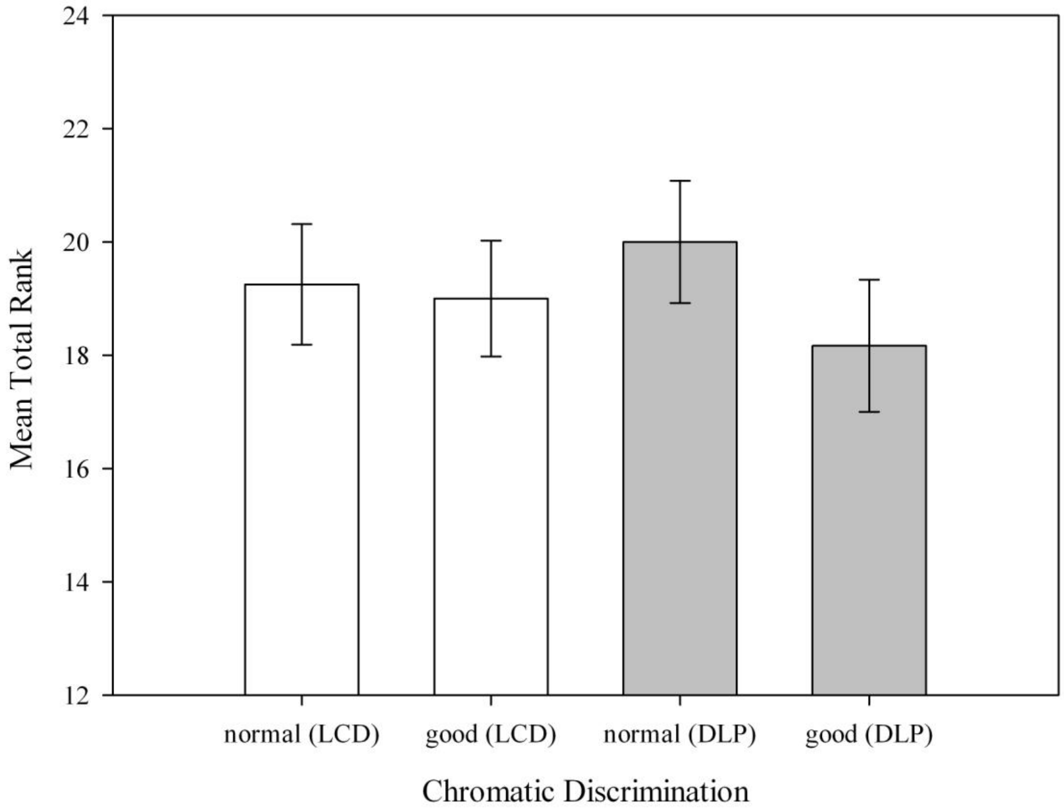

Figure 6-12: The mean total ranking for scores by 6 major symptoms of subjects under LCD (white) and DLP (gray) grouped by chromatic discrimination power.

6.4 Comparison between the results by the Objective and the Subjective

Some of the results are the same for the 3D/2D, LCD/DLP, shutter/polarized and the chromatic discrimination groupings for all and in 3D, 2D, shutter and DLP. The strains of ciliary body caused by watching 3D videos is greater than watching 2D videos, and the questionnaire shows that subjects also feel more serious visual fatigue when viewing 3D content. The DLP causes the ciliary body more strain than the LCD, and the questionnaire shows that subjects also feel more serious visual fatigue when viewing on the DLP system. The shutter system makes the ciliary body more tenseness than the polarized system, and the questionnaire shows that subjects feel a little more visual fatigue when viewing on the shutter system.

With reference to chromatic discrimination, subjects' with normal chromatic discrimination have a tenser ciliary body while viewing 3D videos and especially with shutter glasses and 2D videos and especially on the DLP system, than those with the good. The questionnaire shows that subjects feel more visual discomfort viewing 3D videos especially with shutter glasses and 2D videos especially on the DLP system.

Finally, the △HFC results showed that the ciliary body of subjects with normal chromatic discrimination is more strained than those with the good after viewing 2D content on the LCD and 3D content with polarized glasses, while the visual discomfort for the groups with good and normal chromatic discrimination was almost the same under these two conditions.

Table 6-19: Comparison between result analysis of the objective (△HFC) and subjective indicator (questionnaires)

<table>
<tr><th colspan="4">Same Results</th></tr>
<tr><td colspan="2">Mode</td><td colspan="2">3D > 2D
Shutter > Polarized
DLP > LCD</td></tr>
<tr><td colspan="2">Chromatic Discrimination</td><td colspan="2">All: normal > good
3D: normal > good
2D: normal > good
Shutter: normal > good
DLP: normal > good</td></tr>
<tr><th colspan="4">Different Results</th></tr>
<tr><td colspan="2">Objective</td><td colspan="2">Subjective</td></tr>
<tr><td>Chromatic Discrimination</td><td>Polarized: normal > good
LCD: normal > good</td><td>Chromatic Discrimination</td><td>Polarized: normal ≈ good
LCD: normal ≈ good</td></tr>
</table>

Chapter 7 Discussions, Conclusions, and Future Works

7.1 Discussions

According to the results of the analysis of the Δ HFC and questionnaire, the subjects suffer much more ciliary body strain and visual discomfort while viewing 3D videos than the 2D videos ($p<0.001$). One possible reason could be that the brain has to make more effort to adjust to the 3D variations, so it may affect the neural processing and lead to visual fatigue. Another reason could be that maybe the stereo of the 3D video is not as real when compared with natural vision. The binocular parallax that gives the depth perception let people feel that the stereo effect is excessive, so the accommodation system is overloaded and tension occurs in the ciliary body.

The subjects suffer much more ciliary body tension and visual discomfort while viewing 3D videos with the shutter glasses than with the polarized glasses ($p=0.012$). Because of the shutter system theory, brightness is relatively lower and the frames might glitter so that subjects' ciliary body is relatively tenser. In the marketplace, the polarized system camp claims that their system has no disadvantages over the shutter but the stereo is quite the same, and a market research from DisplaySearch shows that the polarized system's share of the market share is increasing. Nevertheless, further research is needed to confirm the above claims and conjectures.

Thirdly, the ciliary body of subjects suffers more fatigue and visual discomfort while viewing 2D videos on a LCD TV than on the laser projector (DLP) ($p=0.008$). Taking time sharing for example, color break-up may occur and affect people's vision. One conclusion is that the cone and rod cells that discriminate between color and gray levels, and sense the resolution are discrete in the spatial domain. This is similar to the spatial formation method, so, this method makes the ciliary body less tense. Another conjecture is that the ciliary body may have been stimulated more slowly by the spatial formation method than the other method, during the 15 min experiment. So, those questions are worthy of discussion.

Finally, subjects with normal chromatic discrimination power strain their ciliary body more than those with good chromatic discrimination power under each condition (All: p<0.001, 3D: p=0.005, 2D: p=0.04, shutter: 0.024, polarized: p=0.055, LCD: p=0.039, and DLP: p=0.009). This indicates that individual differences do affect the levels of visual fatigue. The reason might be that some parts or mechanism of the visual system in people with worse chromatic discrimination are weaker, hence, the different states of the ciliary body. But from analyzing the questionnaire, it shows that the relationships between chromatic discrimination and visual discomfort and the one between chromatic discrimination and ciliary body tension are not the same in all conditions. Generally, visual comfort is more serious for subjects with normal chromatic discrimination than those with the good, and while watching 3D videos and especially wearing shutter glasses, or watching 2D videos and especially by laser projector (DLP). However, there are no differences while viewing 2D contents on LCD TVs and 3D contents with polarized glasses.

It is obvious that some mismatches occurred in the ∆HFC result analysis and questionnaire under certain conditions. Though different ciliary body conditions were detected, the visual discomfort, as evaluated by the questionnaire, is the same. One explanation is that the questionnaire is a subjective method dependent on subjective cognition for evaluations; hence, the reliability and validity of this method needs to be considered. Perhaps those unobvious differences are due to this indicator's inherent inaccuracies, so it is not effective in diagnosing and comparing the factors that cause visual fatigue or their significance.

Then, the design of questionnaire is a key point to enhance effectiveness. It is hard to evaluate the effects on viewers by different variable because of the unobvious result analysis by 15 symptoms. After evaluation by their mean scores compared to the total mean score, (1) eyestrain, (2) dry eyes, (3) too bright, (7) blurred vision, (14) sleepy feeling and (15) difficulty concentrating are chosen for analysis. Then, it does show some obvious results which match the results by objective measuring. So, changing analysis or calculation method might improve the effectiveness. This could be done through such things as different weighting for each symptom, or redesigning the questionnaire by removing unobvious symptoms.

Another explanation is that although their ciliary body has different tension levels in certain condition, subjects feel the same level of visual discomfort. In other words, even if the different tensions are significant for statistics, they are not significant enough to let subjects feel different levels of visual discomfort.

In conclusion, we consider that the HFC and the level of ciliary body strain can be used to objectively evaluate physiological stress or strain resulting from exertion of the visual system, leading to visual fatigue, which in turn leads to a decrease in the performance of the visual system. Visual discomfort, the subjective part of visual fatigue, can also reflect people's feelings directly, even if the results for the subjective and objective parts may be imbalanced.

7.2 Conclusions

(1) 3D videos cause people more visual fatigue than 2D videos do ($p<0.001$).

(2) The shutter glasses afflict people with more visual fatigue than polarized glasses do ($p=0.012$).

(3) The time sharing method causes people more visual fatigue than the spatial formation method ($p=0.008$).

(4) There is no difference between LED backlighting and mixed LED and LD light sources ($p=0.162$).

(5) People with normal color discrimination power suffer more visual fatigue that those with generally good color discrimination power ($p<0.001$), but the levels of visual discomfort are the same while viewing 2D on LCD TVs, and 3D contents with polarized glasses.

(6) The HFC can indeed evaluate physiological stress or strain resulting objectively from exertion of the visual system, leading to visual fatigue.

7.3 Future Works

HFC is an effective indicator to evaluate the state of the ciliary body and visual fatigue. However, to date, the research devices for visual fatigue are expensive, heavy or not in real-time. In most research, the measurement of visual fatigue is apart from visual stimulation; it cannot record simultaneous signals or be connected directly to the state of the eyes. On the other hand, it is necessary that such a device be applied to monitor visual fatigue so patients may receive medical care or treatment. Therefore, a prospective sensor has been proposed that can be applied to visual fatigue. The function of this sensor was originally applied to the intraocular pressure (IOP) sensor by using inductance. The inductance changes are associated with variations of the anterior corneal curvature radius due to IOP differences. The LC oscillator then transforms the inductance value, the signal is transmitted by an antenna, and is finally read by the exterior readout circuit to achieve a real-time IOP measurement. Whether or not visual fatigue affects the IOP is then considered, in other words, whether visual fatigue signals can be extracted from IOP signals. The development of the sensor is still a work in progress; however, the theoretical derivation and estimates shows that the percentage of inductance variation is about 0.08% per 1 mmHg, so this makes it much harder to realize a readout circuit. In the future, a structure alteration or using a capacitance for sensing could be considered to achieve the measurement and monitoring of real-time visual fatigue.

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Appendix 1

【________Display】 次數：

受測者： 日期： /

計分：1 分~沒有 2 分~稍微 3 分~一般 4 分~強烈 5 分~嚴重

症狀	觀看前	觀看後
眼睛疲勞		
眼乾		
感覺太亮		
眼皮跳動		
覺得眼睛受壓迫		
眼睛持續性疼痛		
眼睛是否感到模糊		
感覺頭痛		
頭感覺沉重		
搖動時會頭痛		
感到暈眩		
感到煩躁		
感覺肩膀僵硬		
感到想睡		
不易集中精神		

Publications

Publications

Conference Papers

1. **Yu-Shun Tang**, Yi-Siang Chen, Wei-De Jeng, and Mang Ou-Yang, "Research of Relation between Visual Fatigue and Displays," *International Conference on Photonics*, Tainan, Taiwan, Dec. 8-10, 2011.

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3. **Yu-Shun Tang**, Wei-De Jeng, Ting-Wei Huang, Mang Ou-Yang, Jin-Chern Chiou, Jeng-Ren Duann, Ching-Hsing Luo, Hong-Yi Huang, and Yi-Wu Tsai, "The Novel Research of Intraocular Pressure Tonometer by Using Inductance Sensor," *IEEE Senor Conference*, Taipei, Taiwan, Oct. 28-31,2012

Patents

1. 歐陽盟，鄭偉德，**湯禹舜**，賴建成，"利用光纖成像之膠囊內視鏡"，專利申請中，中華民國，民國99年。