The effects of lens focus when viewing stereoscopic micro-display images

by

YIP, Chun Kwan

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the thesis examination committee have been made.

Dr. Richard So — Supervisor

Professor Chung-Yee Lee — Head

Department of Industrial Engineering and Logistics Management

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by YIP, Chun Kwan

Department of Industrial Engineering and Logistics Management

The Hong Kong University of Science and Technology

Abstract

When we watch a moving object, our lens accommodate on the focused images, our eyes converge to maintain stereo vision, and our pupil controls the amount of light into our eyes. This is called the triple response of eyes. Although virtual reality (VR) binocular displays can present moving stereoscopic images to a viewer, the triple response cannot be performed in a normal fashion because the lens focuses of these displays are fixed. Biological reviews have hypothesized that this may cause eye fatigue in users of VR displays. However, this remains a hypothesis as there is no empirical data to verify it.

In this study, a wearable binocular display with dynamically adjustable lens focus has been developed. Two experiments have been conducted to verify the effects of appropriately adjusted lens focus on task performance and eye fatigue. Results of the first (preliminary) experiment show that the time required to form a single stereoscopic image is significantly shorter when the lens focus is adjusted to match with the depth cue of the presented stereoscopic images (p<0.05, paired t-test). In the second (main) experiment, when lens focus is set at 200cm, results show that eye tiredness rating is significantly reduced when stereoscopic images are presented with depth cues appropriate to 200cm rather than 40cm

($p<0.01$, ANOVA) even though the apparent size of the images presented at a depth of 40cm are larger. This is an important finding because most commercially available VR binocular displays have fixed lens focus of 200cm. This finding can help to explain the commonly reported eye fatigue problems among users of VR displays. Since technological solutions to implement dynamically adjustable lens focus are emerging, the finding of this thesis provides supporting evidence to justify their development.

1 INTRODUCTION

1.1 Overview of stereoscopic vision

1.1.1 Human eye structure

In this research, we focus on the behavior of the eye. As a starting point, it is therefore necessary to know something about the structure of the human eye. The eyeball is roughly spherical. Light enters the eye through cornea and lens. The amount of light falling on the retina is controlled by the size of the pupil. Accommodation is facilitated by the ciliary muscle in controlling the shape of the lens. The lens focuses the incoming light to form a clear image on the retina. Human have two eyes and their line-of-sight converge on the object that we see,

1.1.2 Peripheral mechanism of accommodation

The lens alter its shape and thus change the eye's refractive power, which is known as accommodation. For near vision, the ciliary muscles contract to squash the lens. For distant vision, the ciliary muscle relaxes and the lens is stretched out. The ability of the eye to accommodate decreases with age. Some studies have suggested that the work done by the ciliary muscle may be a factor in eye discomfort when looking at computer screens (Krueger, 1984[1]; Jaschinski-Kruza, 1988 [2]). It is also believed to be a major cause of asthenopia.

The ciliary muscle is a smooth muscle with ability to rapidly contract and relax that makes it more like skeletal muscles such as the biceps, which can fatigue (Kaufman, 1992 [3]). Indeed, several studies (Ehrlich, 1987 [4]; Owens and Wolf-Kelly, 1987 [5]) have indicated that the ciliary muscle may be susceptible to fatigue.

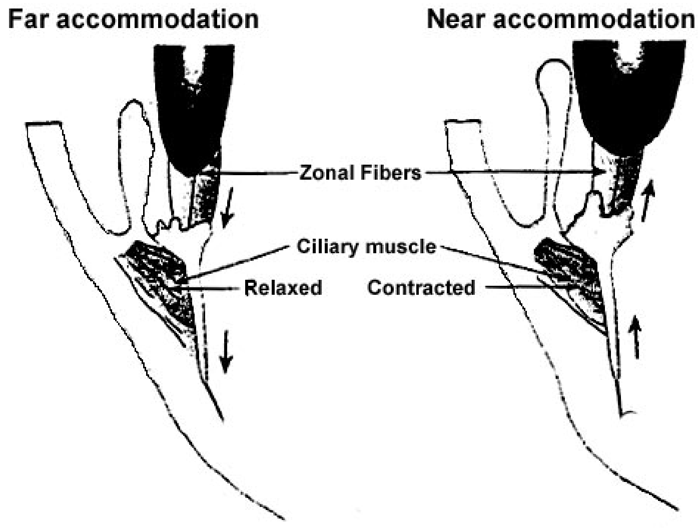

Figure 1.1: Internal mechanism of the eye during accommodation (adapted from Pocock G & Richards, 1999 [6]).

1.1.3 Triple response of the eye

The following section is mainly fact and is adopted from Pocok & Richards, 1999 [6]. When we switch from viewing a far object to viewing a nearer object, and vice versa, the new image is initially out of focus. The blurred image formed on the retina are perceived in the visual cortex as being out of focus, and signals are then sent to the pretectal area and the Edinger-Westphal (accessory oculomotor) nucleus of the brain-stem. The preganglionic fibres from the E-D nucleus drive the postganglionic neurones in the ciliary ganglion, causing the cilliary muscle to contract appropriately to change the shape of the lens..

According to Pocock G & Richards, 1999, triple response occurs when the viewed object is moving. At the same time, the eyes converge by the contraction of the medial rectus muscle. This pathway, which also involves the pretectal and Edinger-Westphal nucleus, helps to bring the image of the object into the fovea of both eyes, which is known as convergence. Another physiological process of the eye that is linked to accommodation is the contraction of the pupils, which accommodation causes to constriction.

1.1.4 Stereopsis and binocular vision

In species with binocular vision, the eyes are separated horizontally and hence receive slightly different views of objects at different distances. The disparate information received is combined with information from the vergence system to provide precise quantitative information about object distance. The perception of depth that is produced by binocular retinal disparity is called stereopsis. Stereopsis is important for producing finely tuned depth perception at near distances (particularly within arms length) when other depth cues are absent. The cortex then forms a stereoscopic single picture based on images from the eyes.

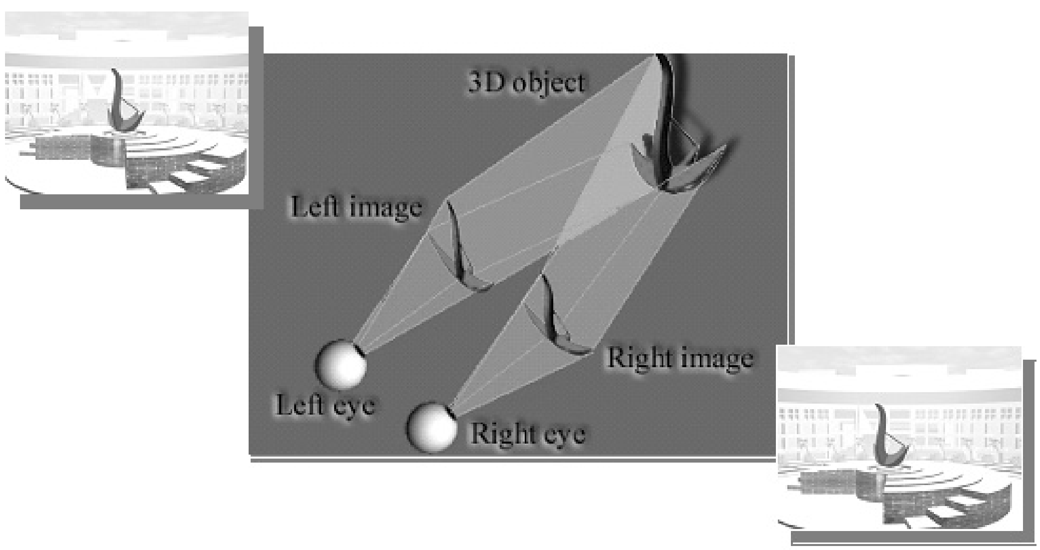

Figure 1.2 In binocular vision, different images are formed by each eye.

1.2 Virtual reality

Virtual-reality (VR) is a technology for presenting 3D images to viewers. The concept dates back more than 50 years to 1956, when Morton Heilig designed the Sensorama (W.R. Sherman, 1995[7]). The Sensorama was one of the first devices to immerse a viewer in a 3D full-color film with ancillary sensations of motion, sound, wind, and smell. VR has since become a means of interacting with computer-simulated environments (S. Das, et. al, 1994[8]). In a typical head-steered VR simulation, images are presented in stereo through a head mounted display (HMD) with head position tracking capability.

In viewing stereoscopic images presented on a typical HMD, the depth of the virtual images is usually fixed at 200 cm because of design constraints. This creates an unnatural situation in which the eyes are asked to converge without the corresponding accommodation actions. It has been reported in several studies (Inoue, Tetsuri, 1997[9], Omori, 2005[10] Eichenlaub, 2005[11]) that the mismatch between accommodation and vergence can create problems in forming stereoscopic vision and that when images are displayed outside the corresponding range of depth of focus, visual fatigue can be induced (S. Yano,2003[12]).

The design of optics in virtual reality devices relies on ray tracing technique. Ray tracing is based on the principle of geometric optics. Light rays from the surfaces of the objects in a scene emanate from all directions, and some pass through pixel positions in the projection plane. As there are an infinite number of ray paths, the contributions to a particular pixel must be determined by tracing a light path backward from the pixel to the scene. Let us first consider the basic ray-tracing algorithm with one ray per pixel, which is equivalent to viewing the scene through a pinhole camera. For each pixel ray, each surface in the scene must be tested to determine whether it is intersected by the ray. If a surface is intersected, then the distance from the pixel to the surface-intersection point can be calculated. The smallest calculated intersection distance identifies the visible surface path (angle of reflection equal to the angle of incidence). If the surface is transparent, then a ray is also sent through the surface in the refraction direction. Reflection and refraction rays are referred to as secondary rays.

This procedure is then repeated for each secondary ray: objects are tested for intersection, and the nearest surface along a secondary ray path is used to recursively produce the next generation of reflection and refraction paths. As the rays from a pixel ricochet through the scene, each successively intersected surface is added to a binary ray-tracing tree. In general, the left branches of the tree represent reflection paths and the right branches represent transmission paths. The maximum depth of the ray-tracing trees is either set as the user position or determined by the amount of storage available. Each path in the tree continues until it reaches the preset maximum, or until the ray hits one of the light sources.

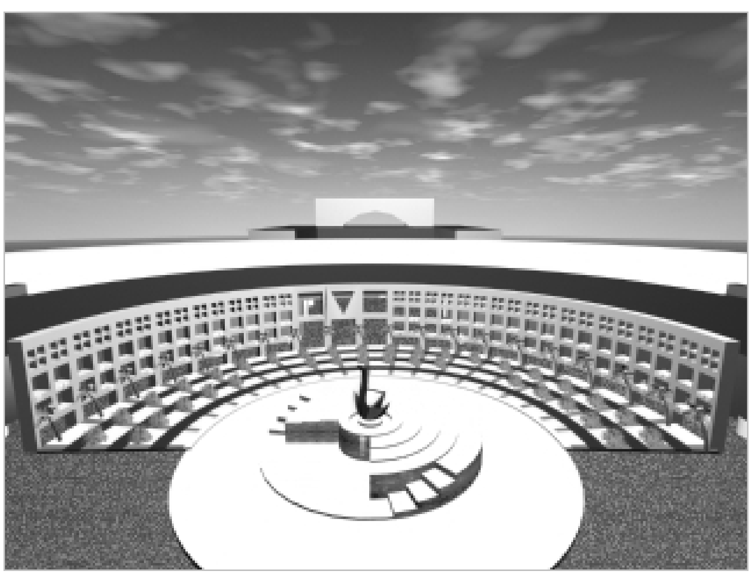

Figure 1.3: Perspective view of a virtual environment.

Stereoscopic vision in VR can be achieved by generating two images from left and right virtual cameras. The image from each camera is then stored in the memory of the VR device and processed in stereoscopic 3D format. The generation of the camera pair is based on the geometric transformation of the base or primary camera (usually the left camera) and the creation of an identical virtual camera with the same focal point. Figure 1.4 shows the schematic diagram for the camera generation. The two cameras are identical and have the same focal point. Figure 1.5 shows a set of images generated from the two virtual cameras in a virtual environment that display a simulation of a real situation to the corresponding eye. Note that there is an angular difference between the two images.

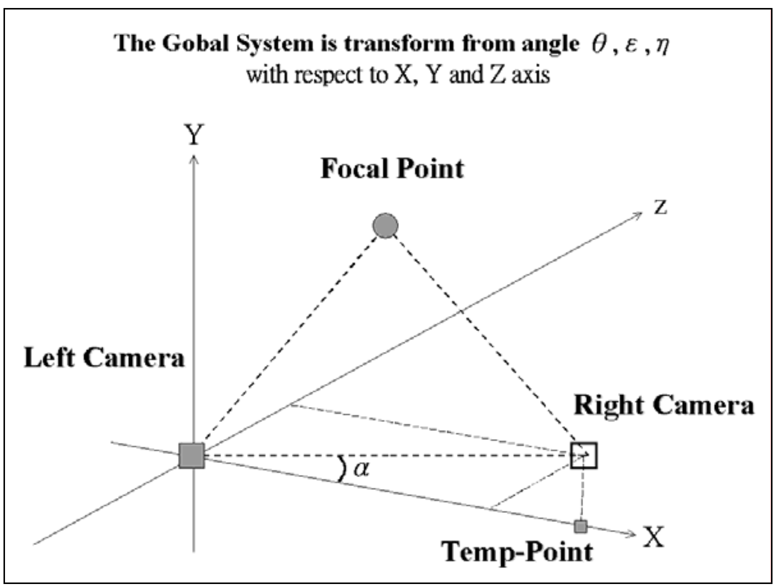

Figure 1.4: Use of a second camera to form a stereoscopic image set

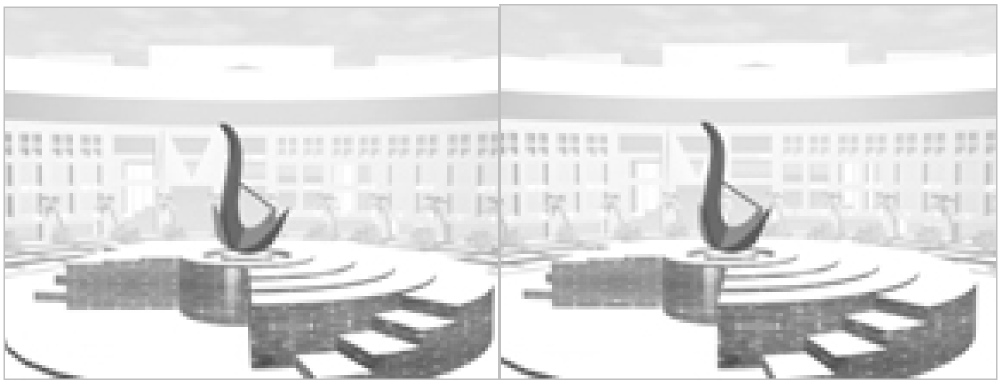

Figure 1.5: A set of stereoscopic images in virtual reality.

1.3 Display systems for stereoscopic vision

There are several types of wearable displays available on the market which is capable to show stereoscopic images. These displays can be divided into shutter glasses systems and mounted display systems. Shutter glasses systems present the stereoscopic image using a specialized device, where the user is required to wear a synchronized blocking device to access the time-multiplexed stereoscopic 3D format. The device can take the form of anaglyph glasses or polarized glasses. These kinds of wearable displays block irrelevant information from the corresponding eye.

In the past, Boom Mounted Displays (BMD), special viewers, or bulky Head Mounted Displays (HMD) were used to view the stereoscopic virtual environment. BMDs are large machines that require the user to sit, stand, or lie down in front of them, and have little mobility, as they are impossible pick up without a hoist.

1.3.1 Head mounted displays for virtual reality

A typical HMD uses different displays to show the image to the left and right eyes. Combinations of lenses are then used to project these images at certain virtual positions in front of the viewer (Deisinger, J., 1996[13]). Studies have shown that the choice of lens and its arrangement are important to ensure correct binocularity when viewing VR images (K. J. Bos, 1998[14], T. Kawai , 2003[15]).

In the early stages of the development of head mounted displays (HMD), a cathode ray tube (CRT) system was used. However, the electronic signals emitted from the CRT hurt the eyes, and its heavy weight caused discomfort to users or hurt their necks. These problems and the disadvantageously high power dissipation of the devices made them unpopular.

1.3.2 Goggle-type wearable displays for virtual reality

Wearable displays were taken forward into a new era by the development of microdisplays. The main advantages of the devices are that they are small with a high resolution and low power consumption. Compact wearable displays available on the market include the GT270 from Canon, the Cy-Visor DH4400 from DaeYang E&C, the I-glasses from I-O Display Systems, the Eye-Trek from Olympus and the Glasstron from Sony.

	DH 4400	I-Glasses3D	FMD-200	PLM-A55	Prototype
LCD	800*600	225*266	320*240	160*240	688*480
Stereo-3D	No	Yes	No	No	Yes
Image Distance	2 Meters	2 Meters	2 Meters	2 Meters	2 Meters
FOV in degree	31.2	30	43	36.5	30

Table 1.1: Comparison of different wearable displays.

1.3.3 General optical system of goggle displays

In this research, a reflective active matrix LCD (AMLCD) microdisplay is used as the display. The basic optical system for this kind of display system is known as an on-axis optical system design. An objective lens is placed between the user and the microdisplay, and a polarized beam splitter (PBS) is then used to polarize and reflect the light down to the AMLCD panel and reflect the display image at the correct polarization.

.

Figure 1.6: Generic on-axis optical system for a typical reflective microdisplay.

1.4 Mismatch with ocular triple response

Most contemporary microdisplay systems only provide fixed lens focus. To achieve binocular vision, therefore, the eyes of viewers need to adjust the vergence to form a single stereoscopic image of an object. The change in vergence is different from actual accommodation, and viewers are forced to perform vergence changes without respective accommodation actions. This action violates the relationship between accommodation and vergence in natural vision (Rushton and Riddell, 1999[16]).

This conflict between accommodation and vergence is thought to be the cause of some of the side effects of using binocular microdisplay images, such as cybersickness and visual fatigue (Wann et al., 1995[17], 1997[18]).

In this study, we investigate whether the matching of the lens focus and stereoscopic depth cues can effectively eliminate this conflict between accommodation and vergence. The work of Kawai (2003) gives a preliminary answer. In an experiment in which the stereoscopic depth range varied between 40 cm and 200 cm, the real-time visual measurements taken during an experimental viewing task indicated that when the image distance (the lens focus in the case of micro-display system) matched the stereoscopic depth cues, the accommodation distance and convergence distance of the participants appeared to be very similar. This finding suggests that the matching of the lens focus with stereoscopic depth cues can indeed successfully eliminate the conflict of accommodation and vergence. However, Kawai did not study the time taken to form a single stereoscopic image, and thus his results need further support, which is the main motivation for this research.

1.5 Specialized terms in the thesis

In addition to the terms lens focus and stereoscopic depth cues, other specialized terms in the field of virtual reality, binocular display, and visual systems are used throughout this thesis. A glossary of terms is therefore presented in the appendix for ease of understanding.

2 LITERATURE REVIEW

2.1 Approaches to Stereoscopic Virtual Reality

Humans determine the difference between stereoscopic 3D vision and 2-and-a-half-D vision by parallax. The information given by the parallax values of image points helps with differentiation. Parallax viewing can be divided into five approaches. The first is zero parallax (Figure 2.1). This is the most common case in normal vision, as human eyes can automatically adjust the focal length to match the focal point of the nearest object. Humans can also control the focal point of their eyes so that they can concentrate on a certain object that may not be the nearest object in the environment. This is the ideal case of stereoscopic 3D vision. The second approach is parallel parallax (Figure 2.1), which occurs when a viewer looks at objects that are a great distance away. In a stereoscopic 3D display, when the IPD equals the length of parallax, then the axes of the eyes will be parallel, just as they are when looking at a distant object in the real world. However, when parallel parallax is used in small screen displays, it produces discomfort.

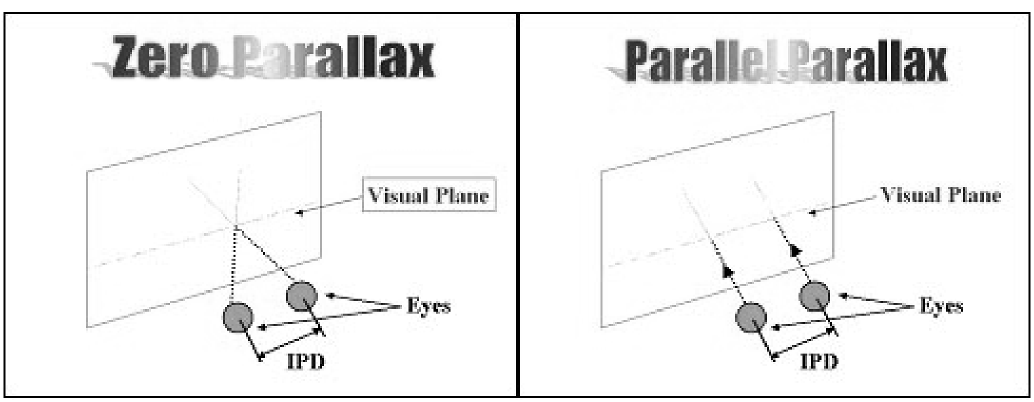

Figure 2.1: Zero Parallax and Parallel Parallax.

Positive converging parallax (Figure 2.2) occurs when viewing a cathode ray tube

(CRT) monitor. Any uncrossed or positive value of parallax will produce images that appear to be within the space of the cathode ray tube (CRT) or behind the screen. With the help of optical equipment, wearable displays can be designed to form a virtual image behind the screen, which is a popular approach. In positive diverging parallax (Figure 2.2), images are separated by a distance that is greater than t. This divergence does not occur when looking at objects in the visual world, and the unusual muscular effort needed to fuse such images may cause discomfort. There is no valid reason for using divergence in computer-generated stereoscopic images.

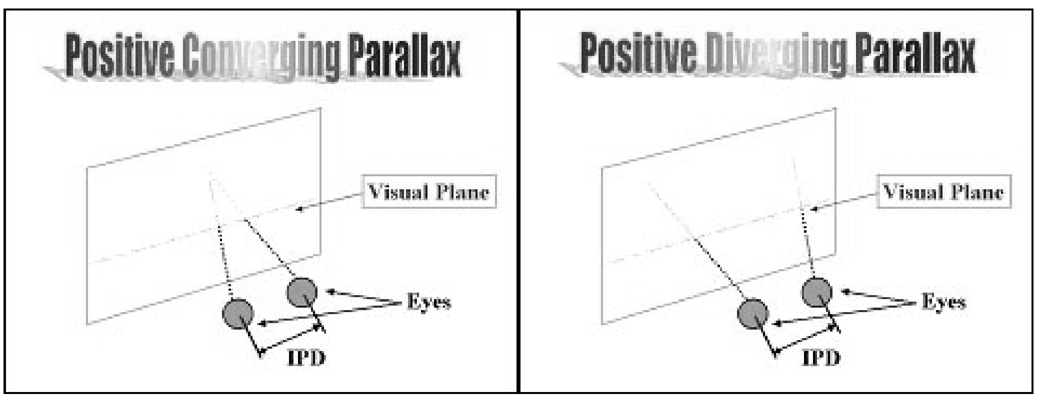

Figure 2.2: Positive converging parallax and positive diverging parallax.

In negative crossed parallax (Figure 2.3), objects with negative parallax appear to be closer than the plane of the screen, or the distance between the observer and the screen. The unusual difference in the angle formed by the two pictures on the eyes causes confusion in the brain, and although the brain can correct this kind of error to form a stereoscopic 3D image, it causes the observer to feel tired and to suffer from headaches.

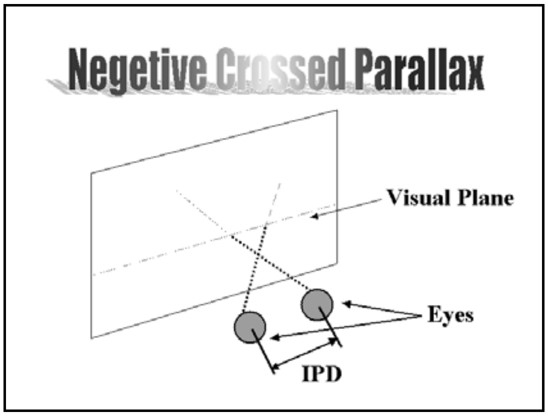

Figure 2.3: Negative crossed parallax.

2.2 Problems in Forming a Single Stereoscopic Image

Eichenlaub (2005) described the problem of the inability to fuse images, or the difficulty in forming a single stereoscopic image due to the conflict between accommodation and vergence. He pointed out that the problem is especially strong with head mounted virtual reality displays (an application of the binocular microdisplay), because the virtual objects are displayed across a wide range of depth. Eichenlaub used several cases to illustrate the problem. For example, he found that in situations in which the lens focus of the head-mounted display is between six feet (around 1.8 m) and infinity, viewers need to converge their eyes to form a single stereoscopic image on a virtual object that is far closer to or further away from the accommodation distance, and that thus “eyestrain may occur or double images may be perceived” (p. 517).

It should be noted that the occurrence of the conflict between accommodation and vergence in stereoscopic HMDs was recognized long before Eichenlaub elucidated the cause (Roscoe, 1987[19], 1988[20]; Wann et al., 1995, 1997).

2.3 Current research findings

Several theories have been advanced to explain the contribution of asthenopia to so-called cyber sickness. Some studies have shown that instrument myopia is created by the tendency of the eye's focus to be altered by the device being looked through. This can lead to inaccurate measurements of refraction, which causes eye fatigue Tetsuri, 1997[21], Omori,, 2005[22].

Another problem with virtual reality simulation is the Mandelbaum effect, which, according to Owens, 1979[23], describes the situation in which far objects appear blurred when viewed through a mesh screen, presumably because accommodation is biased toward the nearer screen. Owens reported this bias to reach a peak when the screen is near the dark focus point. Gleason and Robert 1997[24] found that the Mandelbaum effect is likely to be due to involuntary mis-accommodation .

2.4 Research gap: the need for focus matching

There is one research on the relationship between the link between focusing and tiredness with adjustable IPDs. Shibata and Kawa, 2004[25] presented a paper that describes the development and evaluation of stereoscopic 3-D displays that incorporate a dynamic optical correction mechanism in which the display equalizes the theoretical points of accommodation and convergence. In a related study, Ukai ,2002[26] used video refraction to measure the dynamic properties of the near triad in observers of 3-D displays.

However, the question of whether matching the lens focus with stereoscopic depth cues could effectively eliminate the conflict between accommodation and vergence remains. Shibata (2003) gave a preliminary answer in an experiment in which the stereoscopic depth range was between 40 cm and 200 cm and the real-time visual measurements taking during an experimental viewing task indicated that when the image distance (the lens focus in the case of a microdisplay system) matched the stereoscopic depth cues, the accommodation distance and convergence distance of the participants appeared to be very similar. This finding suggests that the matching of the lens focus with stereoscopic depth cues can successfully eliminate the conflict between accommodation and vergence. However, Shibata did not study the time taken to form a single stereoscopic image, and thus this study seeks to fill this research gap and thereby provide supporting evidence for Shibata's theory.

In the next chapter, the system prototyping of a dynamically adjustable lens focus microdisplay is presented.

3 PRELIMINARY EXPERIMENT

3.1 Objectives and hyptheses

In a typical Head Mounted Display (HMD), the distance between the lens and the display screen is fixed. When viewing stereoscopic images presented on a HMD with different binocular disparities, viewers are forced to perform vergence without appropriate eye accommodation. This posts an un-natural demand on viewers' eyes.

This experiment is conducted to study the benefits of appropriate lens focus adjustment on the time taken for viewers to converge a pair of left and right binocular images into a single stereoscopic image. 3D letters were presented with binocular disparities appropriate to a virtual depth of 40cm. Two lens focus adjustments were used: 40cm and infinity. The order of presenting the two lens focus conditions was randomized.

Participants are required to view stereoscopic virtual images presented on our home-built HMD with the computer-controlled lens focus system. we will study the effect of a matched lens focus in forming a stereoscopic vision from a biocular vision. Our hypothesis on this experiment is that participants took significantly less time to converge the left and right images when the lens focus matched with the virtual depth of the images ($p<0.0001$, ANOVA).

3.2 Methods

3.2.1 Dependent Variables

The dependent variable in this study was the single image formation time. The participants were asked to indicate whether they saw a single or double image through a computerized response system. The maximum duration for the participants to form a single stereoscopic image was 30 seconds. From a pilot trial conducted before this experiment, it was found that most viewers could complete the formation of a single stereoscopic image within 30 seconds. If there was a case where the participant could not form a single stereoscopic image within 30 seconds, for analysis purposes, the single image formation time would be treated as 30 seconds.

3.2.2 Independent Variables

There were two independent variables in the experiment: lens focus and object depth. Two levels of lens focus (40cm and infinity) and two levels of object depth (40cm and 200cm) were used.

3.2.3 Controlled variables

The controlled variables are the environment setting, the apparatus, and the instructions given to the participants. The experiment was approved by the human subject experiment committee at the Hong Kong University of Science and Technology. The experiment is done in the Human Computer Interface lab in HKUST. The experiments were conducted in a dark environment. All windows in the VR are blocked, all lightings are turn off during the experiment. All unnecessary computers and equipment are turn off. All instrument lighting (eg. LEDs) are covered. Door was not accessible from outside to prevent interruption. In order to get the experiment goes smooth, only the experimenter and participate are in the Human Computer Interface lab.

3.2.4 Design of Experiment

The design of the preliminary experiment is a full factorial of the four conditions. There are listed below:

- Condition 1 (Lens focus: 40cm, Image depth 40cm);
- Condition 2 (Lens focus: optical infinity, Image depth 40cm);
- Condition 3 (Lens focus: 40cm, Image depth 200cm);
- Condition 4 (Lens focus: optical infinity, Image depth 200cm).

The experiment was separated into two sessions and used 10 participants. All participants took part in all four conditions that were the full factorial combinations of the two levels of lens focuses and two levels of object depths. After each condition, the participants were asked to rest in complete darkness for five minutes. In each condition, the participants were asked to view a binocular display and form a single stereoscopic image five times. Each stereoscope single image formation was called one dependent repetition.

The presentation order of the four conditions was randomized and was different among participants. After the presentation of the four conditions (each with five dependent repetitions), the whole procedure was repeated two more times (i.e., three repeated blocks (rep_block)). For each participant, the order of presenting the four conditions in each repeated block was the same. In summary, each participant performed three repeated blocks of four conditions with five dependent repetitions in one session.

All participants were asked to come back for a second session after 3 days. The second session had the same experiment sequence as the first session. The presentation sequence of the four conditions for each participant was the same as that of the first session. The separation of three days or more was to reduce any accumulative effect of eye fatigue. Figure 3.1 show the sequence of the preliminary experiment. The symbol “M” means biocular vision, “S” means stereoscopic vision. Participant will be asked to report when they form single vision from stereoscopic image. Each participant repeated the task 10 times. In total, there were 100 data runs that were the exhaustive combination of 5 repetitions, and 10 participants.

M → S	S → M	M → S	S → M	M → S	S → M	M → S	S → M	M →S	S→M
1	2	3	4	5	6	7	8	9	10

Figure 3.1 Figure showing task sequence in the preliminary experiment

3.2.4.1 Task Content

The WorldToolKit™ virtual environment authoring and rendering software was used to generate a synchronized stereoscopic VR simulation. The WorldToolKit™ run on an SGI Infinity-Reality workstation and output the VR simulation in two synchronized stereoscopic VGA streams. Those synchronized stereoscopic VGA streams are then feed into the customized LCD drivers of the home-built HMD. Figure 3.2 illustrates a side-view of a participant viewing the home-built HMD system. The virtual environment contains two 3D words. One of them is placed at 40cm depth from the viewer and the other is place at 200cm. The texts are made up of 3D letters and WorldToolKit™ was used to present the text in appropriate binocular disparities. In this experiment, participants were only asked to read the text placed at the virtual depth of 40cm. Two lens focuses were used: 40cm and infinity. The order of presenting the two lens focus conditions was randomized.

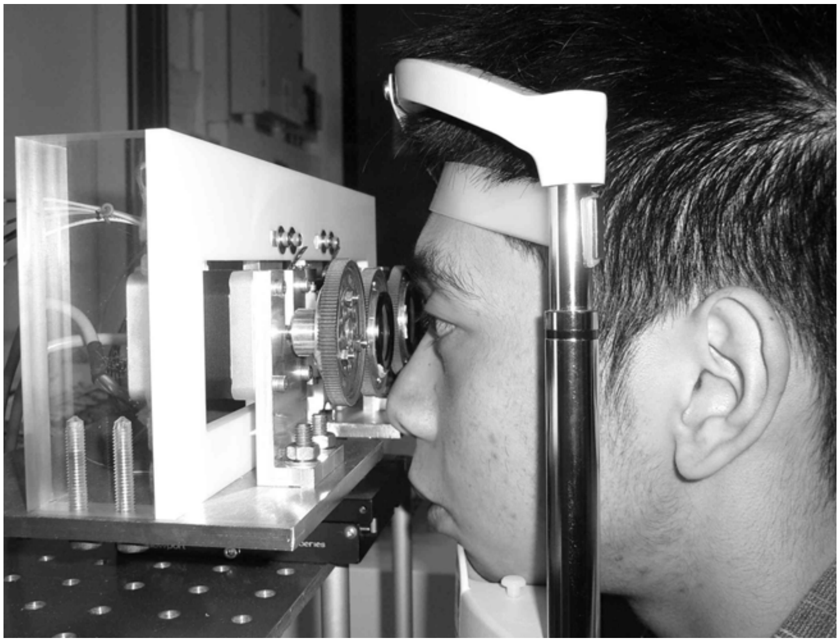

Figure 3.2 Side-view of a participant viewing the home-built HMD system.

The stereoscopic images generated by WorldToolKit™. The images shown the vision for the left eye and right eye. The content of the task consists of the words "HELP ME!" and "PLEASE". The words "HELP ME!" is at a virtual depth of 40cm. The word "PLEASE" is at a virtual depth of 200cm.

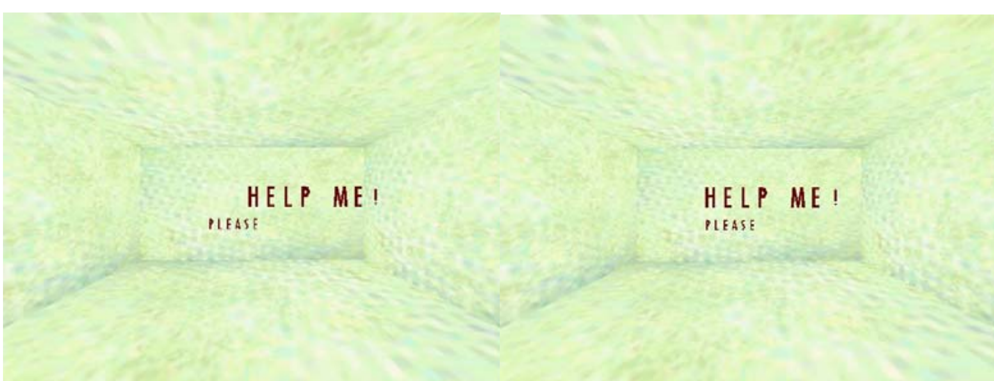

Figure 3.3 The stereoscopic images displays to the eyes.

3.2.4.2 Participants

Ten participants volunteered the experiment (8 males and 2 females). There was no special preference on the gender of the participants. Young adults were preferred and the age of the participants would be kept between 18 and 30. There are several screening criteria concerning the visual parameters of the participants were imposed. The reasons were to ensure that the participants could have sufficient visual ability to see the image sharply, to fuse the binocular images into one single stereoscopic image, and had no serious binocularity problem which avoided them to perform the experiment task.

To qualify for the experiment, participants had to attain visual acuity equaled or more than 20/20 in both near (14 inch, i.e. 36cm) and distance (20 feet, i.e. 6.1 meter) tests, no colour blindness and normal stereopsis (test result 40 seconds of arc or less). Vision screening tests were conducted before the experiment. The vision test OPTEC 2000 from Stereo Optical Co., Inc was used. Only participants who passed the vision screening test were qualified for the experiment.

3.2.5 Stimulus and Apparatus

3.2.5.1 Hardware Overview

HMDs with computer-controlled adjustable lens focuses are not commercially available. Therefore, we have developed our home-built system for this research. This HMD is equipped with computer-controlled lens focuses based on Silicon Microdisplay Technology, Lee et al, 1999[27]. Two liquid-crystal-on-silicon (LCoS) micro-display provided by Integrated Microdisplays Limited (model iSDTV704C) as the display panels and match with our own adjustable optical system.

The two custom-made modules are mounted by an aluminum track to form a dual microdisplay module set which ensures the two optical systems are horizontal aligned. The distance between two modules is adjustable to fit for the inter-pupil distance (IPD) of the user.

The complete set of the equipment is mounted into a chin vest. Users can adjust the support of the chin vest in order to get their eye adjust to the same horizontal level of the dual module set. At the same time, the height of that module set can be adjusted by the corresponding optical plane on top of the core support. Finally, two identical step motors are attached with the lens gear.

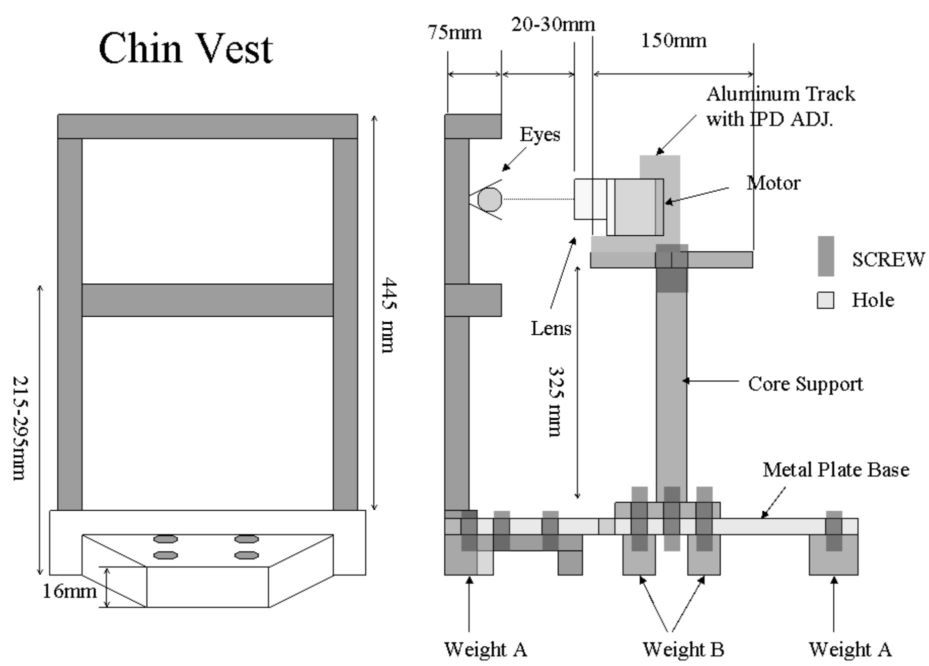

Figure 3.4: A block diagram to show the fixation of the experiment setup

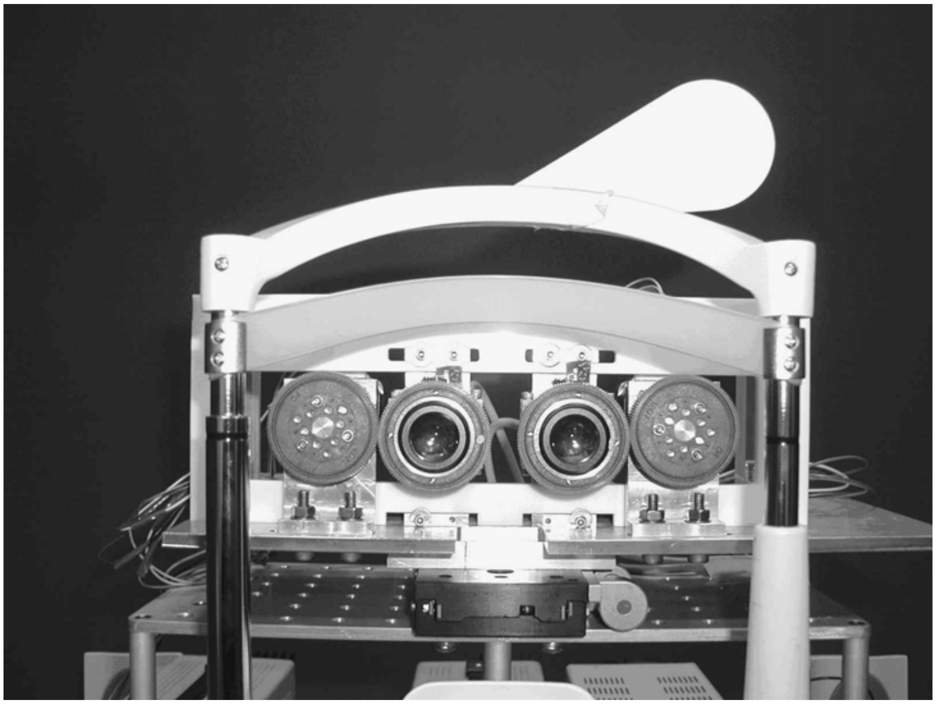

Figure 3.5: A photo showing the front-view of the home-built HMD with lens of adjustable focus. Processor-controlled stepper motors are used to adjust the lens focuses

3.2.5.2 Microdisplay Module

The micro-display units are supplied by Integrated Microdisplays Limited (iMD), Hong Kong, PRC. The model is iSDTV704C which comes with an optical system with fixed focus. The display area is 0.56” diagonally and the resolution is 688 (Horizontal) x 480 (Vertical). It comes with a optical system with field-of-view (FOV) is 30 degree in diagonal. The lens focus is fixed at 200cm. Beam splitter and polarizer slice are used to replace the PBS.

In this research, we have replaced the lens from by our objective lens. We choose to use the objective lens from microscope with higher refractive index and lower angle aberration. At the same time, we have make our own lens module with gear that can fit with our motor control system. The specific design objective is to supply a dynamically adjustable lens focus module which can be assembled on the iMD iSDTV704C micro-display unit and can fulfill the requirements of our designed experiments.

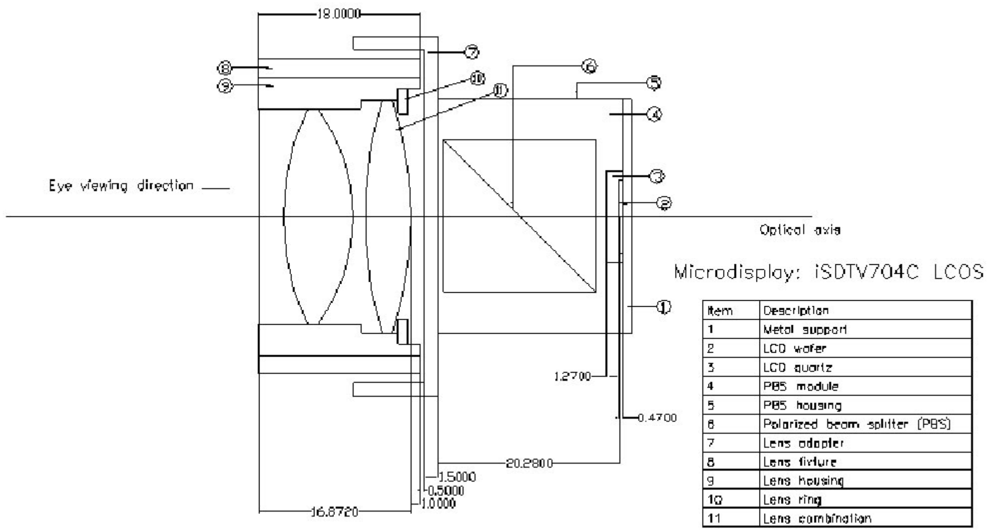

Figure 3.6: The internal structure of the iSDSTV704C microdisplays module (source from Integrated Microdisplays Limited)

In the iSDTV704C module, each LCD display panels work with a sophisticated hardware driver with proprietary driving scheme. Each hardware driver accepts one VGA input stream. In order to get the best quality of image, we choose to dual stream approach which is mentioned in section 0. In the basic set of experiment, we use the dual output video stream from the SGI computer to output the stereoscopic images generated using the software World Tool Kit.

In order to calibrate the equipment, we use spirit level to perform checking equipment and calibrate every parts of the setup are aligned horizontally. Both of the LCD panels will be measured by the PR705 spectrometer, to make sure the color coordinates and color distribution are close.

Figure 3.7: Shows the equipment for our system calibration. The middle picture is a PR705 spectrometer which measure the range of visible frequencies.

3.2.5.3 The optical system

Convex lens is used in the reflective microdisplay system, the image formation will in the virtual plan behind the lens. The virtual image formation distance (D) can be adjustable by changing the distance between the lens and microdisplay (d).

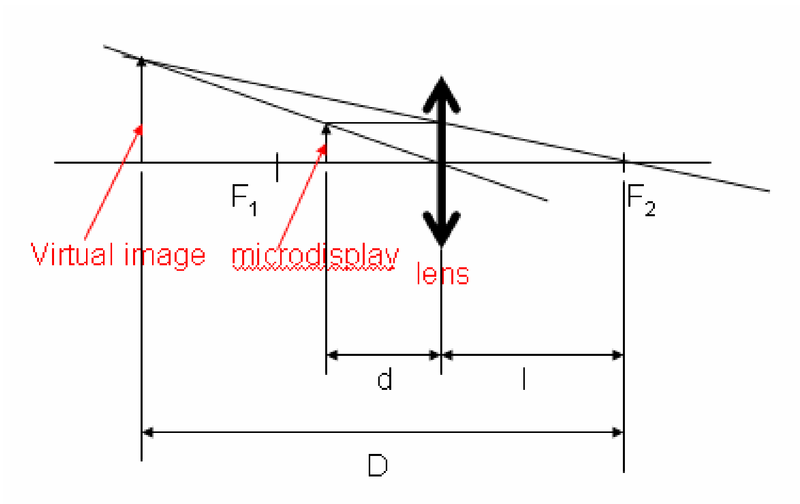

Figure 3.8: The optical design of the microdisplay system in our experimental setup

D = distance from eye to virtual image ,

d = distance from display to lens

F = focal length of lens

l = distance form eye to lens

v = distance from virtual image to lens, where D = v + l

By lens formula, $1/d = 1/v + 1/F_2$ $(F_2 - d)/(dF_2) = 1/v$

$v = (dF_2)/ (F_2 - d)$ .... (Eq. 1)

$D = ((dF_2)/ (F_2 - d)) + l$ .... (Eq. 2)

The relationship between the focus distance of the virtual images and the distance between the LCD micro-display and the lens is described by Melzer and Moffitt (1997)[28]. By positioning the lens at the appropriate position, a desired image focus distance could be obtained. The two figures in next page show the concept of moving of lens in relation with the virtual image distance. We can found that when the lens is moving closer to the microdisplay, the distance of virtual image formation will be closer.

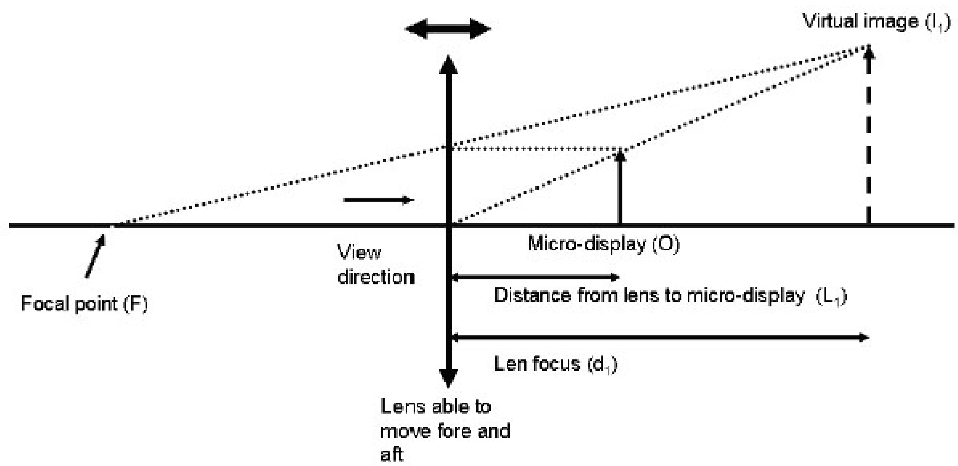

Figure 3.9: A lens diagram to show the formation of a virtual image at the custom-made microdisplay system.

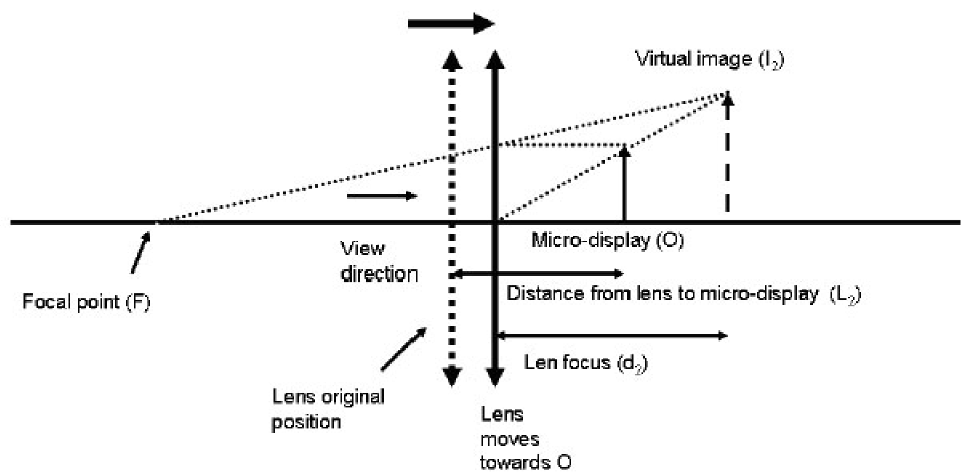

Figure 3.10 A lens diagram to show the change in virtual image formation when the distance between lens and microdisplay has changed

Basically, we need to decide the Near and the Far point of our optical system. In optometry, focus distance of 31cm to 40cm will be use as the best visual acuity distance for near point. The common use of far distance is 200cm. This information is available from the internet in those optometry and neuron-science organizations, like: Investigative Ophthalmology & Visual Science and American Physiological

Society. We choose to use 40cm for the near point because it is the physical limit of our existing optical system. At the same time we choose to use 200cm as the far point because it is also commonly found in all those wearable display setup mentioned previous section. Meanwhile, we get confirmed from two optometrists in PolyU before we confirmed the two parameters.

3.2.5.4 Electro-mechanical part

As mention in previous section, two identical step motors are mounted with a gear system which can alter the distance between the microdisplay and the lens. The position of each lens system was controlled by a stepper motor via gear arrangements. The stepper motor has a step rate of 1.8 degree per step. Through the gear design, each revolution of the motor corresponding to a change of 0.5mm in the distance between the lens and the LCD panels. For every revolution, it will be divided into 200 steps and each step change can adjust the lens position by 0.0025mm. Gears were mounted to the lens and the stepper motor, and both gears were engaged. One revolution of stepper motor would lead to one revolution of lens.

Microcontroller unit (MCU) was used to control the turning of the stepper motor. The turning motion lead will lead to an angular displacement of gear and alter the distance between the lens and microdisplay. The angular displacement for each step of the stepper motor was 1.8 degree. Each of the stepper motor are control by it own driver circuitry and MCU control board. The two control boards are connected by another control circuitry. Figure 3.11 shows the block diagram of the electro-optic system.

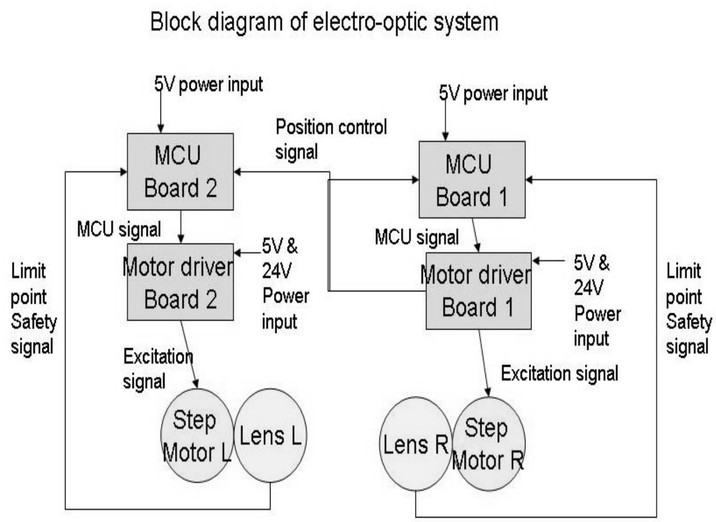

Figure 3.11: A block diagram of the electro-optic system. Two identical sets of MCU controlled motor system are attached to the lens for the left and the right eye. The program inside the two MCUs is identical, which was customized for this micro-display system. The program accepts the control signals from the user circuitry and sent out control signal to the stepper motor driver circuit in order to make the stepper motor move. The control signals from user are defined in 3 states, Reset, Near and Far. The corresponding meaning is initialize the lens to our pre-defined position, set lens focus at far (40cm) and set lens focus at (200cm).

Finally, precise inter-pupillary distance (IPD) can be customized for each individual. The inward and outward movement of the lens was achieved through a screw and thread design. The lens was held by a lens fixture which had an external thread (a male part). A lens adapter (a female part), which had an internal thread on its wall surface, allowed the lens fixture to screw in. One revolution of the lens fixture corresponded to a lens movement of 0.5mm to or from the micro-display screen. The movement of the lens was driven by a stepper motor via gear arrangements.

The system had been verified by comparing the marked symbol with several camera systems with same optical setting before experimental use. The detail of the report is attached in the appendix. Figure 3.12 shows the complete experiment system.

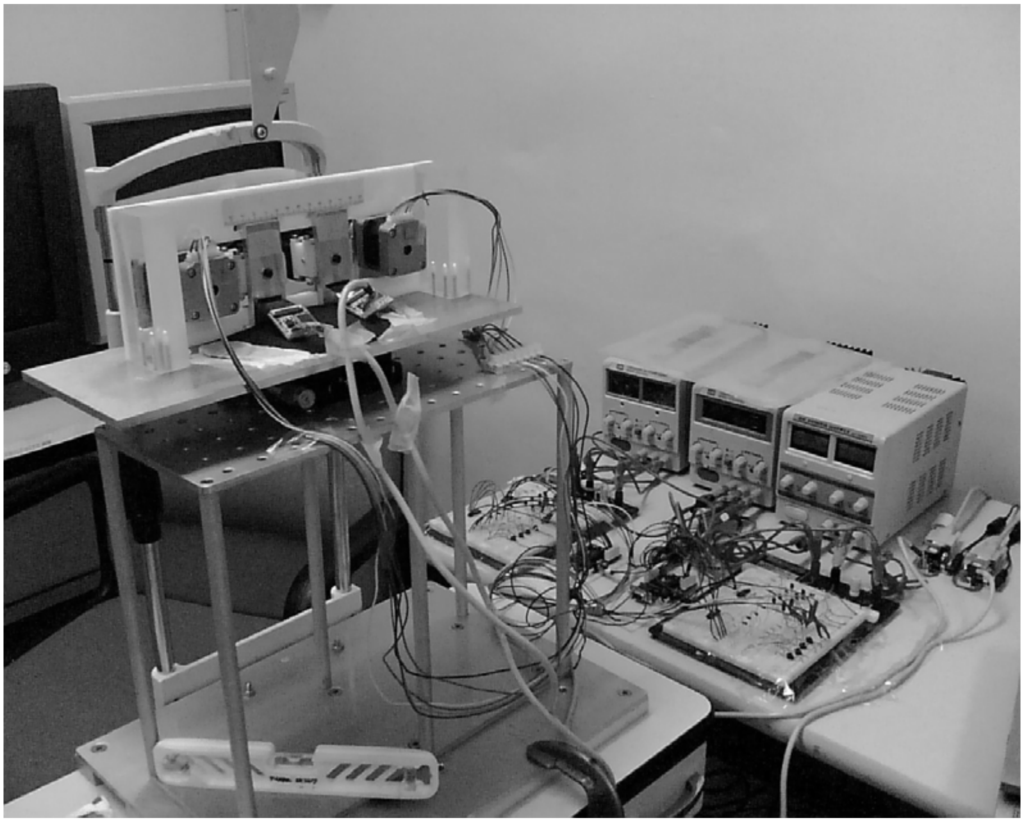

Figure 3.12: An overview of the complete experiment system, independent power supplies are allocated for each identical driving circuit

3.2.6 Procedure

All the participants gave written consent and declared to have no visual problem. They were then tested for their visual acuity. The concept of double vision and vergence were explained to them. Before the experiment, the Inter-Pupil Distance (IPD) was customized and a chin and forehead rest was used to fix the position of the participant's head. The alignment between the lens and the participant's left and right eyes were then adjusted individually.

As explained in the previous section, each participant took part in 10 data runs that were 5 repetitions of 2 conditions. At the beginning of each condition, the participants were shown a biocular image (the same image for both eyes) at a pre-arranged optical depth (40cm or infinity). The participants had to press a respond button when they saw a single image. Then, the experimenter would present the stereo (i.e., binocular) images at the same optical depth after a non-constant delay time between 3 to 20 seconds. The participants were instructed to release the respond button as long as they saw double images.

When the participants had indicated that they have seen single images for about 10 seconds, the stereo images were reset to the biocular image after another non-constant delay time in the range of 3 to 20 seconds. This process was repeated five times for each of the two lens focus conditions. The use of non-constant delay times avoid a repeated regular schedule that can be detected by the participants. The time between the moment the stereo images were presented and the first instance the participants pressed the respond button was measured as the time taken to converge the stereo images into a single image. This time is referred to as the 'single image formation time'.

For those participants who failed to merge the stereo images into a single image within 30 seconds, the stereoscopic images were reset to the biocular image for the next repetition. In this case, the time taken to turn the stereo images into a single image was recorded as 30 seconds. Two minutes of rest were given to the participants after 5 repetitions of the same condition. During the rest, the participants were asked to take off the HMD and relax their eyes in a dark environment.

3.3 Results and Analyses

The main dependent variable measured was the single image formation time. Each participant took part in 10 data runs that were 5 repetitions of 2 conditions. Ten participants volunteered the experiment (8 males and 2 females). Their ages range from 23 to 43. Each participant repeated the task 5 times. In total, there were 100 data runs that were the exhaustive combination of 2 lens focus, 5 repetitions, and 10 participants.

In each run of condition, the 5 repetitions were considered as dependent repeated measures. These 5 measurement data were averaged to a better mean data estimation for further analyses. Therefore, the size of the data set in the data analyses was 240 (i.e. 1 mean data for each condition * 3 Rep_block * 2 Sessions * 10 participants).

Initially, the results data were analyzed using parametric test. If the nature of the data did not comply with the assumptions of parametric test, for example the data was not normally distributed, non-parametric test would be applied to verify the findings in the parametric test.

3.3.1 Data Distribution

The single image formation times were tested for their normalities. Box-Cox transformation, $\lambda = -1$, was applied to transform the data distribution to a normal distribution. From the normal probability plot (Figure 3.13), the transformed data appeared to be approximately normal. The normality of the transformed data was much improved than that of the non-transformed data. The transformed data were used in the sub-sequent analyses of variance (ANOVAs).

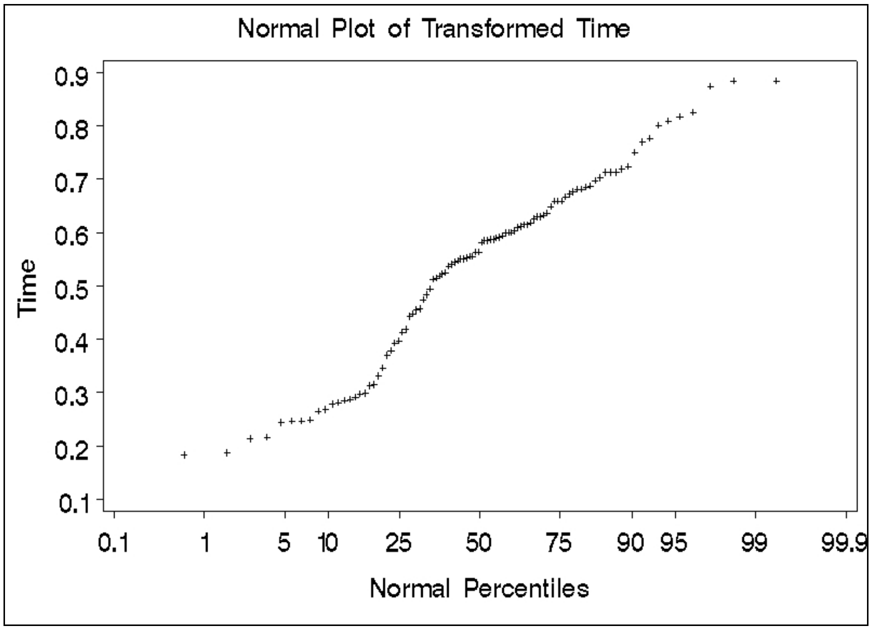

Figure 3.13: The normal probability plot of the time (transformed by Box-Cox transformation, λ=-1) taken for each participant to converge the left and right stereoscopic views of a virtual image at a depth of 40cm with two lens focus (40cm and infinity).

3.3.2 Main effects of Lens Focus and Repetition

In this experiment, the time taken for each participant to converge the left and right stereoscopic views of a virtual image (single image formation time) was the only dependent variable.

The lens focus, participant and repetition were the independent variables. Figure 3.14 illustrates the main effect of lens focus. It can be observed that the lens focus contributed to a large reduction in the median single image formation times when the virtual image with 40cm depth was presented at a lens focus of 40cm. Median data were shown in Figure 3.14 because the time taken to converge the two stereo images did not follow a normal distribution before the Box-Cox transformation.

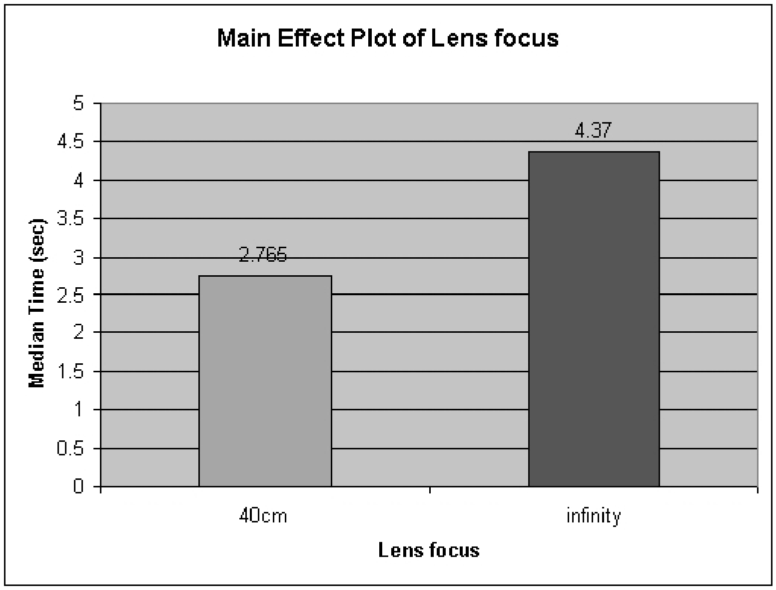

Figure 3.14: Median time of 10 participants (sec.) taken to converge the left and right stereoscopic views of a virtual image at a virtual depth of 40cm.

The effect of repetition was less obvious. In Figure 3.15, the median single image formation time at Repetition 1 appeared to be higher than those of Repetitions 2 to 5.

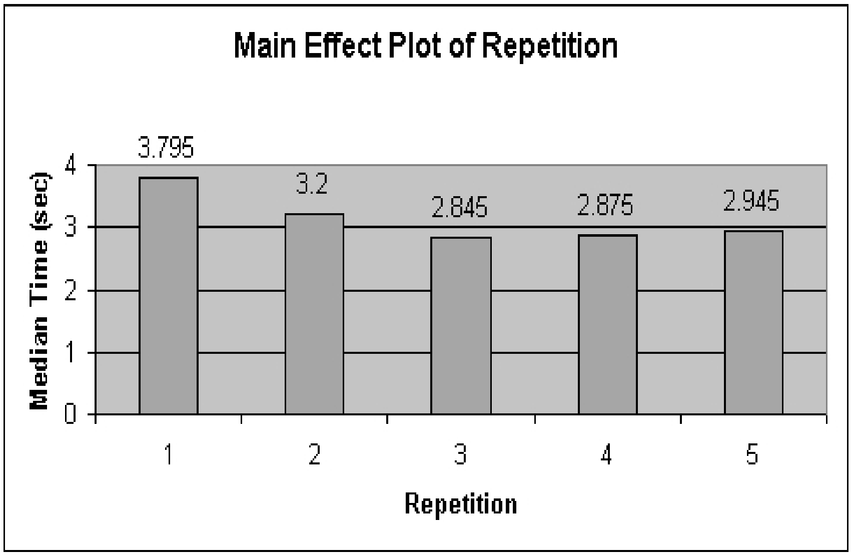

Figure 3.15: Median time of 10 participants (sec.) taken to converge the left and right stereoscopic views of a virtual image at a virtual depth of 40cm as functions of repetition (1 to 5).

3.3.3 Results of ANOVA

From the ANOVA result, both the main effects of participant and lens focus were statistically significant ($p<0.0001$). The effect of repetition was also significant ($p<0.005$). For the interaction effects, the interaction between the effects of participant and the effects of lens focus was significant ($P<0.0001$). On the other hand, the interaction between the effects of participant and the effects of repetition as well as between the effects of lens focus and the effects of repetition were both not significant ($p>0.15$).

Source	DF	Pr > F
Lensfocus	**1**	**<.0001**
Repetition	**4**	**0.0038**
Lens focus*Repetition	**4**	**0.2213**

Table 3.1: Summary of the Analysis of Variance (ANOVA) Table for the time (transformed by Box-Cox transformation, λ=-1) taken to converge the left and right stereoscopic views of a virtual image at a depth of 40cm.

The significant main effects of lens focus and repetition were further analyzed by Student-Newman-Keuls (SNK) Test (alpha=0.05). For the factor of lens focus, the time taken to converge the left and right stereoscopic views of a virtual image at a depth of 40cm at matched lens focus (i.e. lens focus at 40cm) was significantly smaller than that of at un-matched lens focus (i.e. lens focus at infinity). For the factor of repetition, the single image formation time collected at repetition 1 was significantly longer than those collected at repetitions 2 to 5. There was no significant difference in the single image formation times collected for repetitions 2 to 5 (Table 3.2: Result of SNK Test on the difference of effect at the different levels of repetition. Means with the same letter are not significantly different. The mean value is the Box-Cox transformed converge time (unit is sec-1).).

Means with the same letter are not significantly different.

SNK Grouping	Mean	N	Repetition
A	0.55893	20	3
A			
A	0.55354	20	5
A			
A	0.53845	20	2
A			
A	0.53557	20	4
B	0.50118	20	1

Table 3.2: Result of SNK Test on the difference of effect at the different levels of repetition. Means with the same letter are not significantly different. The mean

value is the Box-Cox transformed converge time (unit is sec^{-1}).

3.3.4 Examinations of interactions effects

The two-way interactions between different factors: lens focus, repetition and participant are studied by analyzing their interaction plots. Figure 3.16 illustrates the interaction effect between the effects of lens focus and the effects of repetition. It can be observed that the effects of lens focus collected at repetitions 1, 2 and 4 form almost parallel lines. Although the effects of lens focus collected at repetition 3 and 5 crossed each other and crossed the others lines, the trend that participants took shorter time to form a single image when the lens focus matched with the depth of the virtual image was maintained in all repetitions. This is consistent with the ANOVA result that there was no significant interaction between the effect of lens focus and repetition.

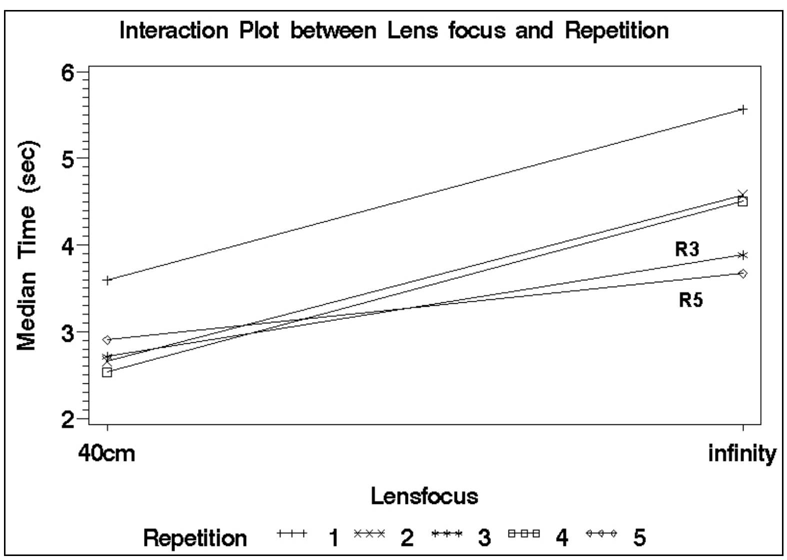

Figure 3.16: Interaction plot between the main effects of lens focus (40cm and infinity) and the main effects of repetition (1 to 5) on median time taken for 10 participants to converge the left and right stereoscopic views of a virtual image at a

depth of 40cm.

Figure 3.17 illustrates the interaction effects between the main effects of repetition and participant. While some participants (e.g., P3) appear to have larger variations in their performance at different repetitions, other participants (e.g., P4 and others) follow the median trend of the effects of repetition.

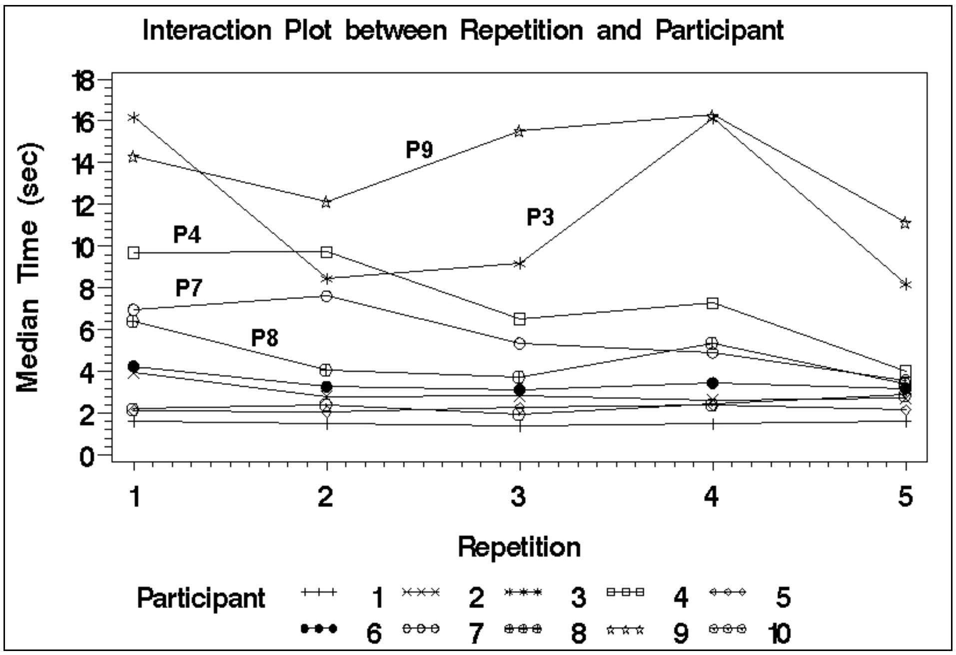

Figure 3.17: An interaction plot between the main effects of repetition (1 to 5) and the main effects of participant (1 to 10) on median time taken for each participant to converge the left and right stereoscopic views of a virtual image at a depth of 40cm with two lens focus (40cm and infinity).

Figure 3.18 illustrates the interaction between the effects of lens focus and the effects of participant. It can be observed that the ten participants can be divided into two groups: (i) data collected from P3, P4, P7, P8, and P9 show a large main effect of lens focus and (ii) data collected from P1, P2, P5, P6, and P10 show a smaller main effect of lens focus. Further studies to explore the possible reason(s) are needed.

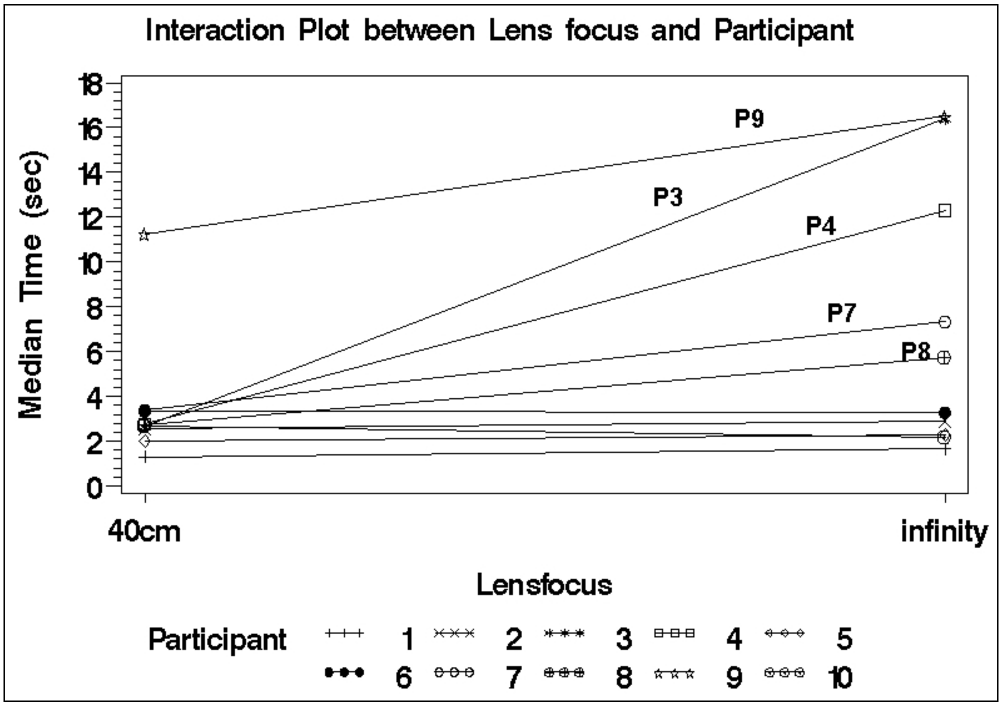

Figure 3.18: An interaction plot between the main effects of lens focus (40cm and infinity) and the main effects of participant (1 to 10) on median time taken for each participant to converge the left and right stereoscopic views of a virtual image at a depth of 40cm.

4 MAIN EXPERIMENT

4.1 Objectives and hypotheses

This experiment is target to study the effect of matched and un-matched lens in different conditions of lens focus and object depth. The user tiredness, occulomotor score and the change of dark focus will be record. Our hypothesis is that matching of lens focus with image depth can significant reduces the tiredness.

4.2 Method

4.2.1 Dependent Variables

In this experiment, we will use 3 dependent variables. The SSQ result in oculomotor section for Pre & Post experiment from Prof. Robert Kennedy. Which is the well know method of cyber-sickness for decades.

The second variable is the 7-point tiredness rating (see Appendix 6.4.1). The third variable is the dark focuses of the eyes. We will use the dark focus of right eye as suggested by the optometrist. User will be asked for the tiredness rating and wait until the rating become zero before the experiment. At the beginning of the experiment, SSQ score and dark focus will be measure. During the experiment, every sub-task will be finished within 2 minutes and they will be asked again their status of tiredness at that moment. The experiment will last for 30 minutes, 16 data of the tiredness rating will be record from t0 to t16. After the experiment, SSQ score and dark focus will be measure again.

4.2.2 Independent Variables

There were two independent variables in the experiment: lens focus and object depth. Two levels of lens focus (40cm and 200cm) and two levels of object depth (40cm and 200cm) were used.

4.2.3 Controlled Variables

The experiment is conducted in the teaching lab of Dept. of Optometry in The Hong Kong Polytechnic University. Experiment setup is placed at the corner of the room and it is connect to the controller PC. Light blocker had been place to the gap of the partitions and doors.

Figure 4.1 Environmental Setting on the optometry teaching lab in PolyU.

During the experiment all lights will be shut down during the experiment. All LCD monitor will be turn off and LED indictors in different electronic devices were blocked. Infrared optometer is used for dark focus measurement. It is placed next to the setup, so that subject can smooth move to the seat for experiment after the dark focus measurement. In the opposite corner to the apparatus, one video cam with the DVD recorder as shown in Figure 4.2.

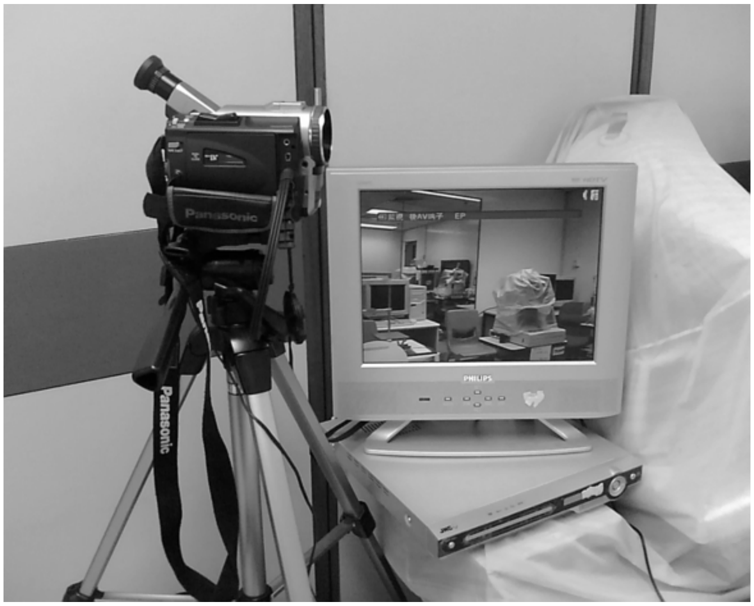

Figure 4.2: The monitor system for the main experiment. It consists of a camcorder and a DVD writer to record the experiment.

4.2.4 Design of Experiment

The is a 2x2 full factorial test, 4 conditions. The two factors are lens focus and Image Depth. Each factor got a level of 40cm and 200cm, thus form the 4 conditions.

		Lens	
		40cm	200cm
Image	40cm	Condition 1	Condition 2
	200cm	Condition 3	Condition 4

Table 4.1: A matrix to show the definition of each condition for the experiment

In every day of experiment, we have divided time slot into AM and PM set. Each set will further divided into two slots. In order to minimize the learning effect, each experiment period of particular participant is separated by at least 6 days. And the second experiment time will be kept in either in the morning or afternoon set.

4.2.4.1 Test Content

The image files are generated by 3D Studio Max, every object is created by the corresponding scale. We have created a cubic box of 200cm and a set of stereoscopic camera in the middle of the outer-most surface of the box. The camera set simulates the two eyes, the distance with distance 55-70mm which fit with the

IPD of each individual subject.

In this experiment, Landolt-C is used. A Landolt C, also known as a Landolt ring or Landolt broken ring, is an optotype, i.e. a standardized symbol used for testing vision. It consists of a ring that has a gap, thus looking similar to the letter C. The gap can be at various positions (usually left, right, bottom, top and the 45° positions in between) and the task of the tested person is to decide on which side the gap is facing.

Inside the environment, we have create five landolt “c” locate in the middle horizontal lines of the display, where the cameras are located at the same line. Each of them is randomly faced in different directions. There are two landolt “c” in the middle vertical axis, which serve as a reference to help participate to form single image. There are 10 sets of combinations. In order to help subject to form an single image, there is one landolt “c” (facing the right hand side) on the top and bottom of the third “c” of the five “c”.

Figure 4.4 show an example of both eye with image distance 40cm and IPD setting 65cm. Those landolt “c” are placed in 40 cm or 200 cm apart from the camera set. There is a text “120” place at the bottom right corner at 120cm part from the camera. The geometrical difference on those landolt “c” set and the reference text “120” and be saw.. This text is used to be the reference for the depth. The top view of the floor plan is shown in below.

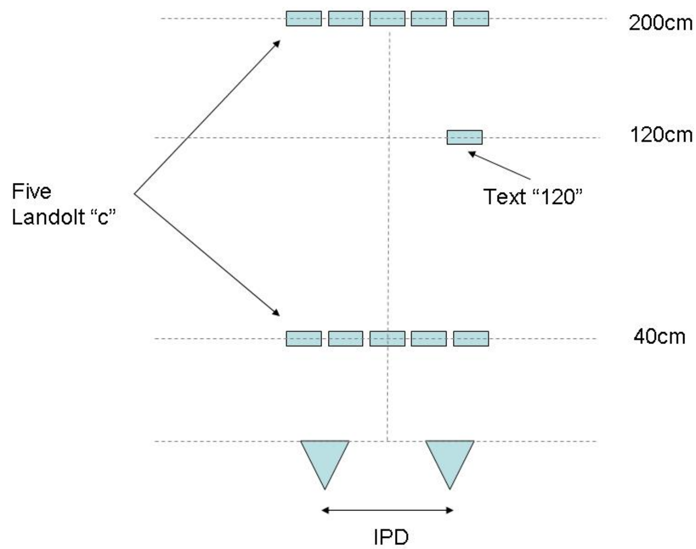

Figure 4.3 The conceptual design for the position of different objects in the virtual environment for the experiment.

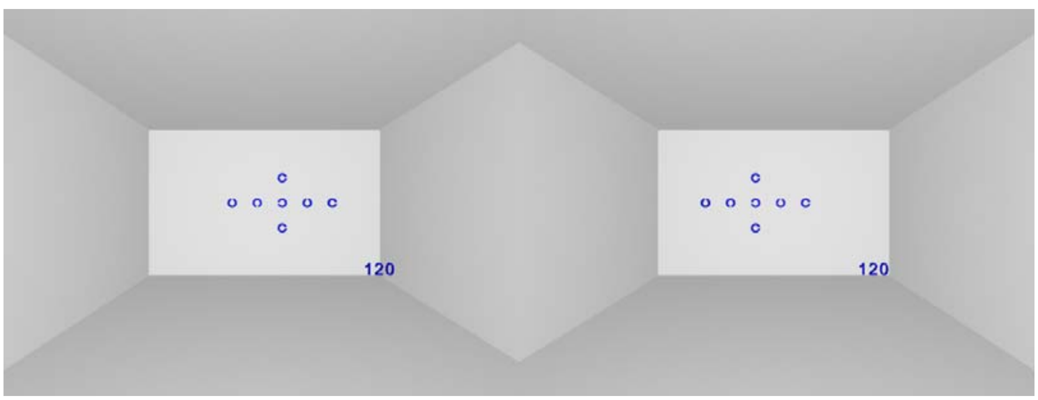

Figure 4.4 An example of the combined Left Eye and Right Eye view with Text distance 40cm and IPD57cm.

We have generated the test content for every IPD values corresponding to each of those participate. In different text depth, we will adjust the size of the text in order to get the same apparent size the same. The size that appears to be a tree in the distance may have an apparent height equal to the length of your thumb at arms length. Finally, the generated image set will then put into a MS power-point file for display.

4.2.4.2 Participants

There were 9 subjects in the experiment, and two randomization restrictions were imposed on each subject: image distance and lens focus. Each subject will have his/her own randomized condition sequence. Those subjects were graduate or post-graduate students, with ages ranging between 22 and 30 (Mean 25, SD = 2). The IPD for close distance (40cm) is 57 to 65 cm. The IPD for far distance (200cm) is 59.5 to 68.5 cm. All of them had passed the selection criteria of color blindness and stereo depth ability. Their parameter of astigmatism, IPD value, Phoria and Visual acuity status had been recorded down.

We have a set of criteria for selecting volunteers. Their age will be in the range of 18 to 30 years old. There is no criterion for gender selection but preferably half male half female. There are no selection criteria for race during recruitment but preferably Hong Kong Chinese because it is easier for reading the instruction and better communication during the experiment. The participant can wear glasses or contact lens for correction of eyesight.

We will select those participate with normal vision which can be corrected by glasses or contact lens. This should be conforming to the standard of visually healthy, that mean no eye or visual problem currently and no serious eye / visual problem before. Participate should be health for not suffered from any serious illness, diabetics or epilepsy. They should not under medical treatment or suffering disability which affects one’s daily life. Then participates will go through a set of eye measure and require passing the following criteria in the aspect of normal vision using the retinoscope and the related test equipment. The following parameters will be measured and the requirement is listed.

Parameters	**Requirement**
Visual acuity both eyes,	attains 1.0 or above
Visual acuity single right eye	attains 1.0 or above
Visual acuity single left eye	attains 1.0 or above
Vertical Phoria (at far and near)	< 0.5 prism diopter
Lateral phoria at far	< 10 prism diopter
Lateral phoria at near	< 20 prism diopter
Stereopsis: accepted depth perception	attains 50 sec of arc or smaller
Stereopsis: threshold depth perception	20 sec of arc
Color blindness	No color blindness

Table 4.2 Show the list of parameters and the corresponding requirement for the selection of the participates

There are four male and five female participates in the main experiment. Three males and three females participates are corrected short-sightedness. One male and two female participants are in corrected long-sightedness. The male participant with long sightedness does not normally wear glasses.

VA - Right eye	Stereopsis (min of arc)
VA - Left eye	IPD (mm) @ 40cm
Color-Blindness	IPD (mm) @ 200cm
Lateral Phoria @ Distant	IPD (mm) @ inf
Lateral Phoria @ Near	Glasses -R
Verical Phoria @ Distance	Glasses -L
Verical Phoria @ Near	Measure -R
Lateral Phoria @ Near	Glasses -L

Table 4.3: The parameters measure for each participate, it included the IPD of the participant in different object distance.

4.2.5 Stimuli and Apparatus

The apparatus of the main experiment is same as the preliminary experiment.

4.2.6 Procedure

Dr. Patrick Ting, an optometrist from PolyU. He will perform the optometry measurement during the experiment. Before the experiment, there is pre-treatment measurement take place at the optometry teaching lab on the 5/F in PolyU. It will measure the following parameters by the sequence below:

1. VA at far and near
2. Laterial phoria at far and near
3. Vertical phoria at far and far
4. Fixation disparity
5. Stereopsis
6. Dark Focus (by autorefractor; baseline at bright environment and then continuously measurement at complete darkness for 5 min)

The second steps will be the pre-exposure refractive error in complete darkness, which is SPH + CYL/2 (SPH and CYL are measured in complete darkness before seeing micro-display) every 30 seconds take one data, measurement last for 5 mins, so 10 data was obtained. When the experiment start. A set of stereoscopic slides will be shown to the subject, each slide consists of 5 Landolt "c" located in same horizontal line. For each Landolt "c", its opening could be face in four different directions (Up, Down, Left, Right) randomly. The 5 Landolt "c", from the left to the right.

After subject can form the single image, he/she need to present verbally for the direction of those five Landolt "c" in the middle line. Experimenter will record the subject's response time and his/her answer. Another randomized slide will be shown to the subject and repeat the previous procedure. This will repeat until every 2 minutes before the next tiredness and SSQ question is asked.

The post-treatment measurement will be also take place in the optometry teaching lab in PolyU 5/F. It will measure the following parameters by the sequence below:

1. Dark Focus (by autorefractor; baseline at bright environment and then continuously measurement at complete darkness for 5 min)
2. Laterial phoria at far and near
3. Vertical phoria at far and far
4. Fixation disparity
5. Stereopsis
6. VA at far and near

4.3 Results and Analyses

In the main experiment, a total of 9 subjects * 4 conditions * 16 data samples = 576 samples are collected. In every condition of each subject, we will take the average of the tiredness rating for analysis. There are 36 data points for ANOVA.

4.3.1 Data distributions

The assumptions of ANOVA are normality, constant variance and independence of the data. As such the normality of the data set (with 36 data points) is examined using normality plots. The p-value smaller than 0.05 leads to the rejection to the null hypothesis that the data is normally distributed. Figure 4.5 shows the probability plot of the average tiredness rating. From the residual Plots for the average tiredness in Figure 4.6, it is found that the residual values are randomized. Figure 4.7, we can see the condition 4 (len focus=200cm, image depth=200cm) has the lowest tiredness rating of 0.82. Condition 3 (len focus =40cm, image depth =200cm) has the highest tiredness rating of 1.696.

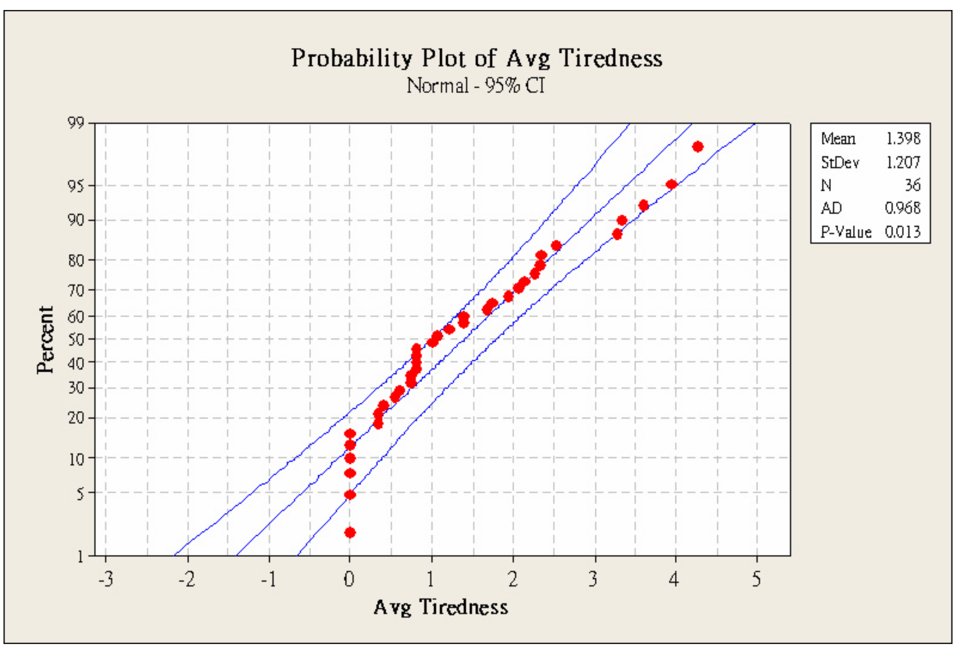

Figure 4.5: The probability plot of the average tiredness rating.

Figure 4.6 Residual plots for the average tiredness

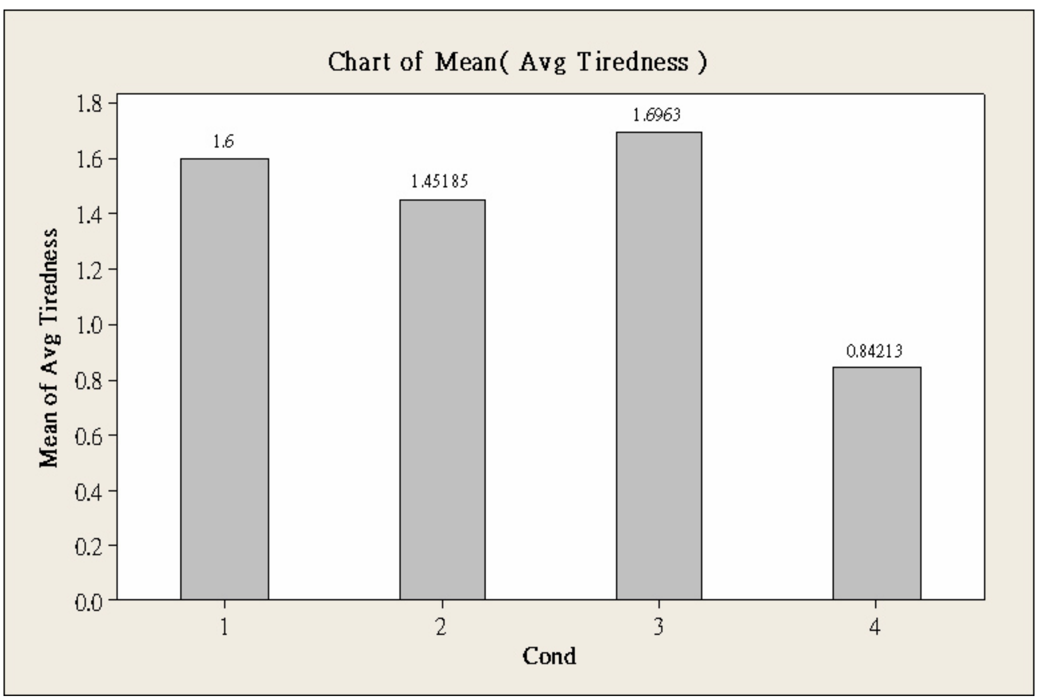

Figure 4.7 Chart of Mean of average tiredness rating for four different conditions.

In Figure 4.7, we can found that the average tiredness of condition 1 and 3 (Lens =

40 cm) is larger than the condition 2 and 4 (lens = 200 cm). The results of the tiredness are possibly influence by the accommodation on eye. In resting status of the eye, the accommodation would be as far point which is around 2 meters. In condition 1 and 3, since the lens focus is fixed at 40 cm, it can explain that eye will get tire easier as it is not the normal fashion of the eye.

4.3.2 Summary of the hypotheses in the main experiment

It was hypothesized that the participants would take significantly give a lower tiredness rating when the lens focus was matched with the image depth. When the lens focus matched with the image depth, the participants did not need to use extra positive or negative fusional convergence ability to overcome the conflict between accommodation and vergence. Consequently, the participants could perform triple response in a normal fashion. Because there were factorials combinations of the lens focus and object depth, four hypotheses (H1 – H4) were formed.

The relationship between different hypotheses and conditions are shown in Figure 4.8. In order to have a brief idea of those hypotheses, a summary of mean of average tiredness rating for each hypothesis are listed in Figure 4.9. In the figure, we can found that significant difference of mean of average tiredness for matched and unmatched condition can be found in H2 and H4. There is no big difference of Avg. tiredness for Match and Unmatched condition for H1 and H3.

H1: At lens focus 40cm, the tiredness rating in matched condition was significantly lower than an unmatched condition

H2: At lens focus 200cm, the tiredness rating in matched condition was significantly lower than an unmatched condition

H3: At image depth 40cm, the tiredness rating in matched condition was significantly lower than an unmatched condition

H4: At image depth 200cm, the tiredness rating in matched condition was significantly lower than an unmatched condition

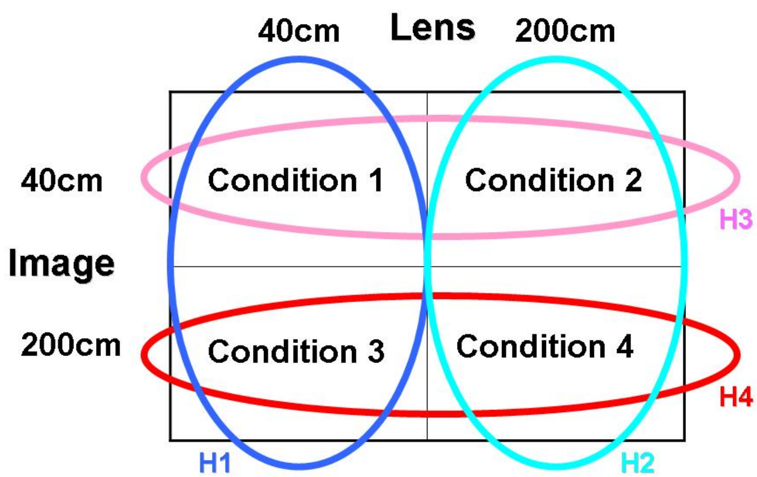

Figure 4.8 Definition of different hypotheses in relationship with different condition

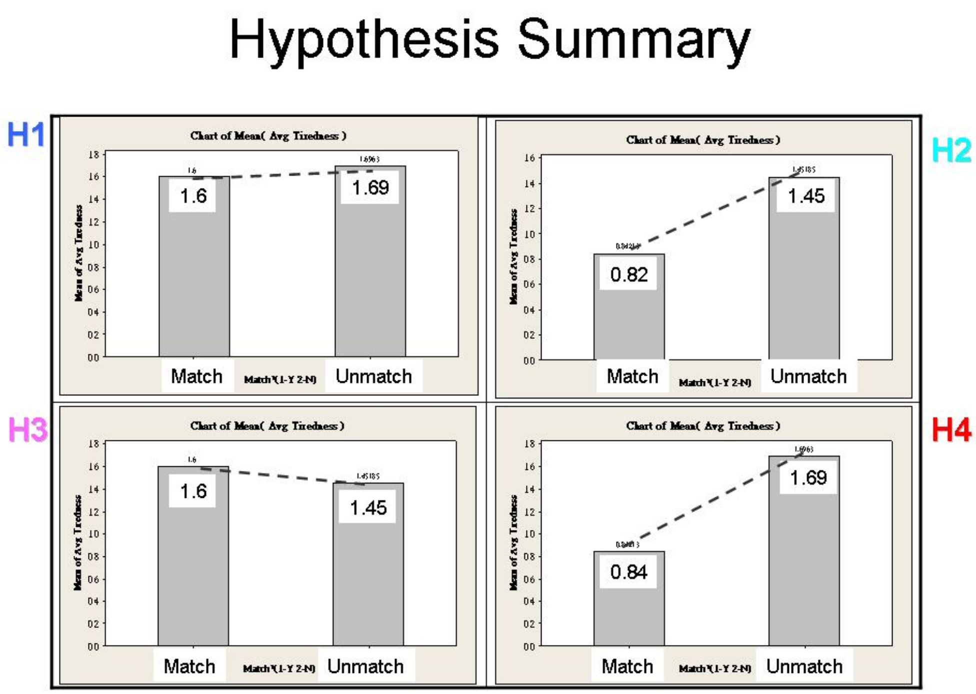

Figure 4.9 A summary of the mean of average tiredness rating for all hypotheses. In H1 and H3, the difference of mean of average tiredness of match condition and unmatched condition is within 10%. In H2 and H4, the difference of mean of average tiredness of match condition and unmatched condition is larger than 70%.

The results show that short-sighted participants tired more easily during the experiment, but were also the group that experienced the greatest reduction in tiredness under the matched condition. Interestingly, the male group also showed a greater reduction in tiredness under the matched condition. It will be further discussed in Chapter 5.

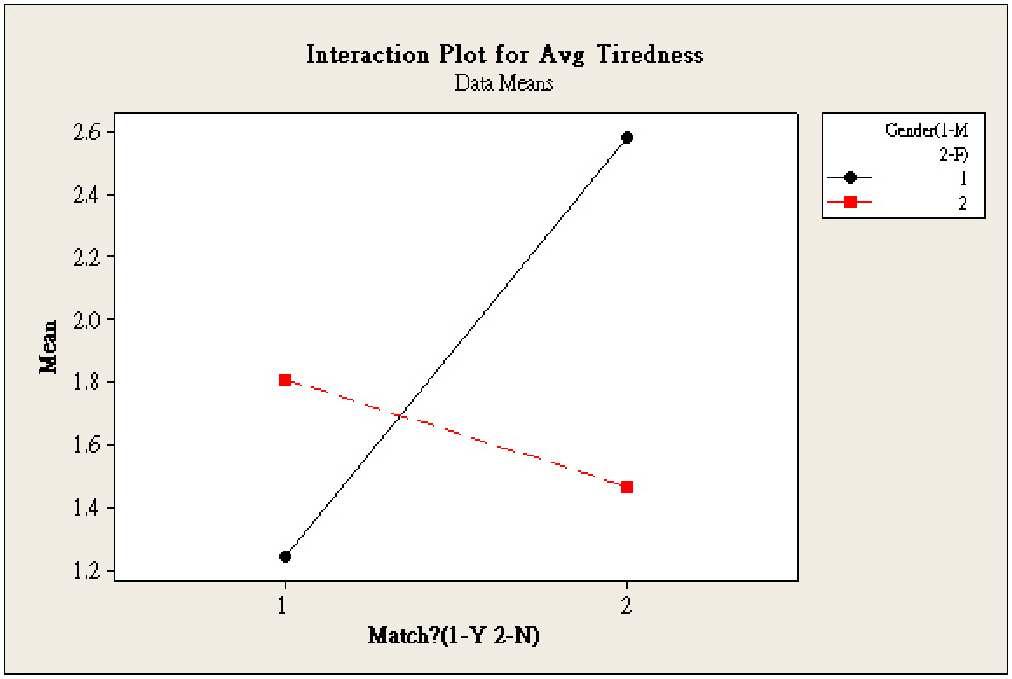

Figure 4.10 Interaction plots between effects of matching and gender using only data from male short-sightedness and female short-sightedness

ANOVA result of MALE with Short Sightedness

Analysis of Variance for Avg Tiredness, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Match?(1-Y 2-N)	1	5.333	5.333	5.333	3.68	0.084
Error	10	14.501	14.501	1.450		
Total	11	19.834				

Table 4.4 ANOVA result of MALE with Short Sightedness

ANOVA result of FEMALE with Short Sightedness

Analysis of Variance for Avg Tiredness, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Match?(1-Y 2-N)	1	0.349	0.349	0.349	0.22	0.650
Error	10	15.893	15.893	1.589		
Total	11	16.242				

Table 4.5 ANOVA result of FEMALE with Short Sightedness

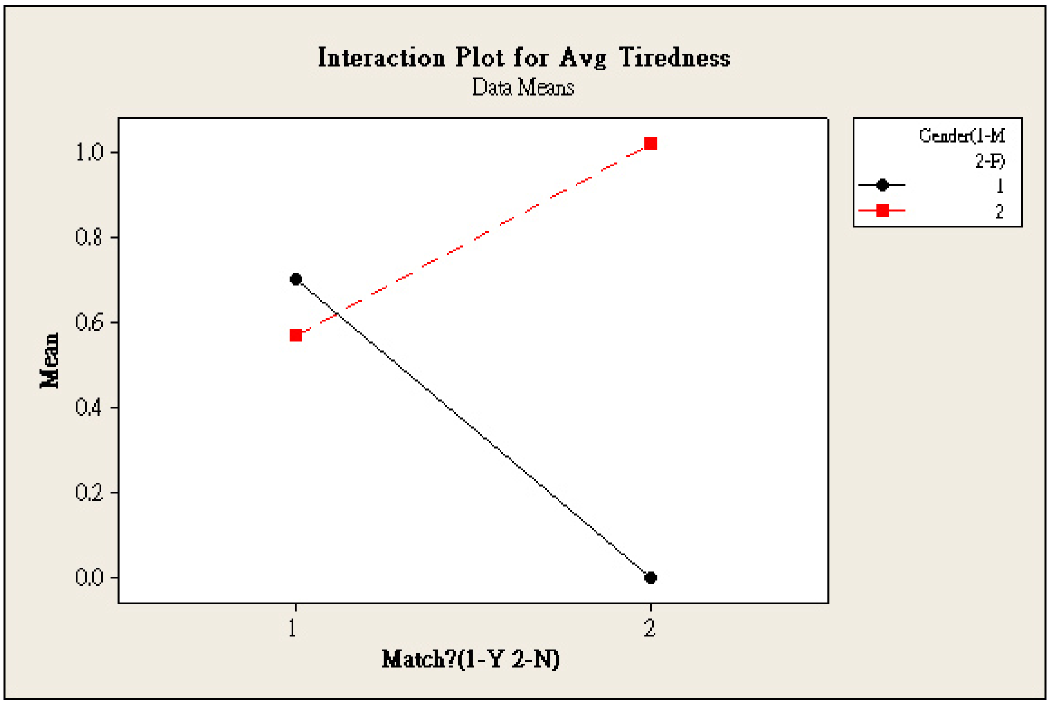

Figure 4.11 Plot the interaction plots between effects of matching and gender using only data from male long-sightedness and female long-sightedness

ANOVA result of MALE with Long Sightedness(1 subject)

Analysis of Variance for Avg Tiredness, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Match?(1-Y 2-N)	1	0.4900	0.4900	0.4900	1.00	0.423
Error	2	0.9800	0.9800	0.4900		
Total	3	1.4700				

Table 4.6 ANOVA result of MALE with Long Sightedness (1 subject)

ANOVA result of FEMALE with Long Sightedness (2 subjects)

Analysis of Variance for Avg Tiredness, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Match?(1-Y 2-N)	1	0.4050	0.4050	0.4050	1.33	0.292
Error	6	1.8211	1.8211	0.3035		
Total	7	2.2261				

Table 4.7 ANOVA result of FEMALE with Long Sightedness (2 subjects)

4.3.3 Hypothesis 2 (lens focus = 200cm): ANOVA

The sight/sightedness in the ANOVA is referring to the corrected sightedness with contact lens or glasses. From the ANOVA result, we can found that the main effects: image depth, duration and sightedness are statistically significant with P<0.001. Gender is not significant. There are three two-way interactions effects: ImageDepth with Gender, ImageDepth with Duration and Gender with Sightedness.

Dependent Variable: Tire

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	66	285.0055556	4.3182660	3.99	<.0001
Error	221	238.9944444	1.0814228		
Corrected Total	287	524.0000000			

R-Square	Coeff Var	Root MSE	Tire Mean
0.543904	95.99214	1.039915	1.083333

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Imagedepth	1	22.2222222	22.2222222	20.55	<.0001
Gender	1	0.0390625	0.0390625	0.04	0.8494
Duration	15	130.5555556	8.7037037	8.05	<.0001
Sight	1	68.0625000	68.0625000	62.94	<.0001
Imagedepth*Gender	1	12.1918403	12.1918403	11.27	0.0009
Imagedepth*Duration	15	9.0000000	0.6000000	0.55	0.9064
Imagedepth*Sight	1	9.5069444	9.5069444	8.79	0.0034
Gender*Duration	15	1.7303819	0.1153588	0.11	1.0000
Gender*Sight	1	7.4817708	7.4817708	6.92	0.0091
Duration*Sight	15	24.2152778	1.6143519	1.49	0.1092

Figure 4.12 ANOVA result of hypothesis 2 (lens focus = 200cm). The main effects: image depth, duration and sightedness are statistically significant with P<0.001. Gender is not significant.

4.3.3.1 Hypothesis 2: Main Effect - Image Depth

Wilcoxon two-sample tests are done for each main effect as the data is not normalized. The result in Figure 4.13 shows that image depth is statistically significant in H2 which is consistence with the ANOVA result.

```
        Wilcoxon Two-Sample Test

Statistic                 18499.5000

Normal Approximation
Z                            -3.4746
One-Sided Pr <  Z             0.0003
Two-Sided Pr > |Z|            0.0005

t Approximation
One-Sided Pr <  Z             0.0003
Two-Sided Pr > |Z|            0.0006

Z includes a continuity correction of 0.5.
```

Figure 4.13 Wilcoxon Two-Sample Test for Image depth, result shows that image depth is statistically significant in H2.

4.3.3.2 Hypothesis 2: Main Effect - Duration

Figure 4.14 show that the tiredness rating of the matched condition is always lower than the unmatched one when time goes on.

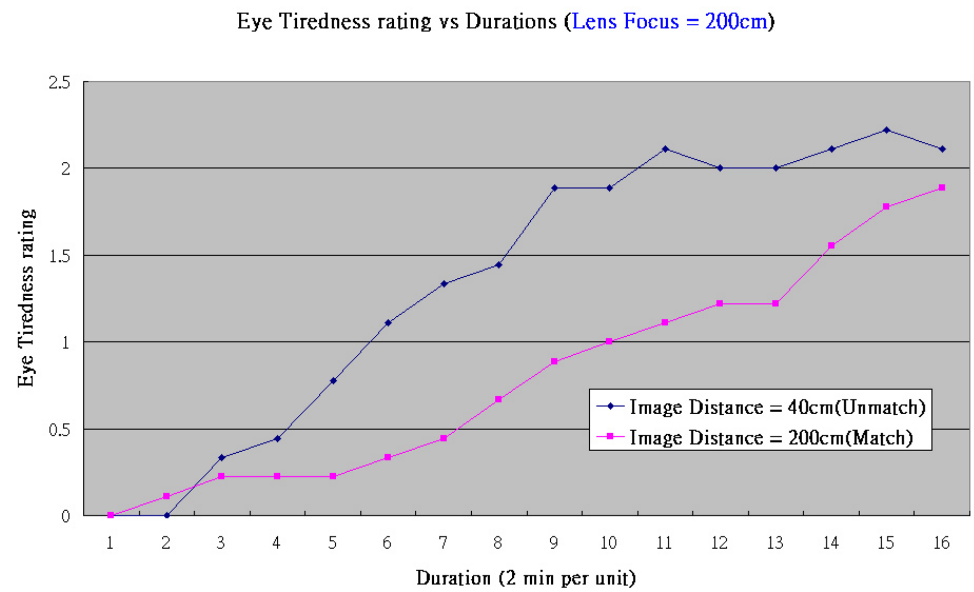

Figure 4.14 Average tiredness rating verse duration for different condition in H2

4.3.3.3 Hypothesis 2: Main Effect - Eye sightedness

Wilcoxon two-sample tests are done for each main effect as the data is not normalized. The result in Figure 4.15 shows that corrected eye sightedness is statistically significant in H2 which is consistence with the ANOVA result. Figure 4.16 shows that participant with short sightedness are easier to get tired than the participants with long sightedness.

```
         Wilcoxon Two-Sample Test

      Statistic             9996.0000

      Normal Approximation
      Z                       -6.1884
      One-Sided Pr <  Z        <.0001
      Two-Sided Pr > |Z|       <.0001

      t Approximation
      One-Sided Pr <  Z        <.0001
      Two-Sided Pr > |Z|       <.0001

  Z includes a continuity correction of 0.5.
```

Figure 4.15 Wilcoxon Two-Sample Test for corrected eye sightedness, result shows that eye sightedness is statistically significant in H2.

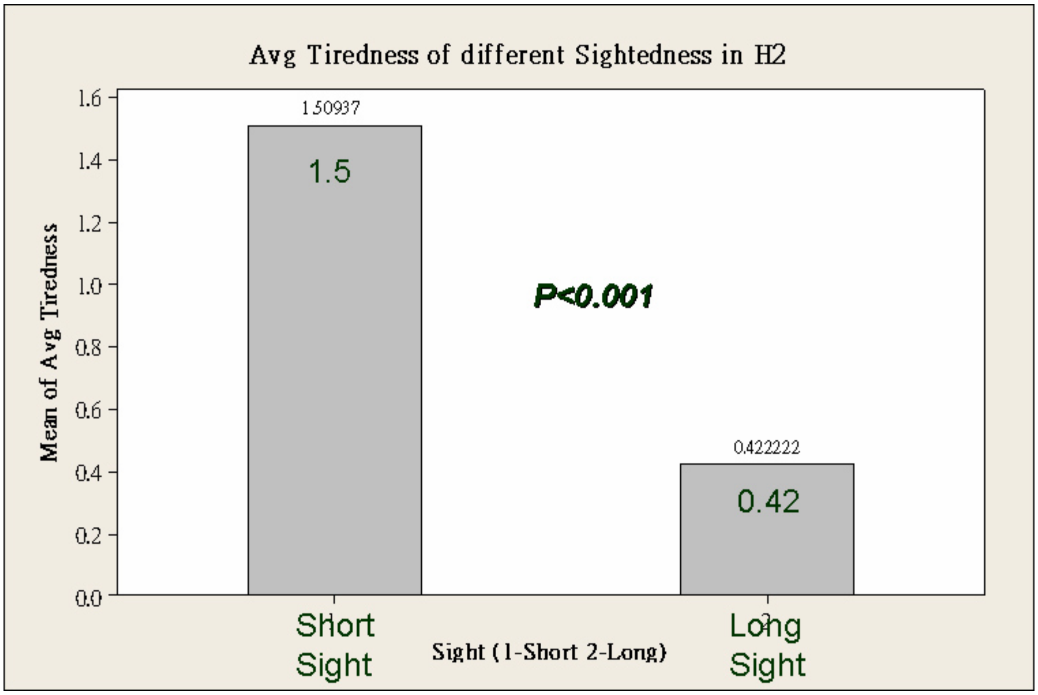

Figure 4.16 Average tiredness of different sighted status in H2

4.3.3.4 Hypothesis 2: Interaction Effect – Gender vs Image Depth

Male participants have larger response to matched condition.

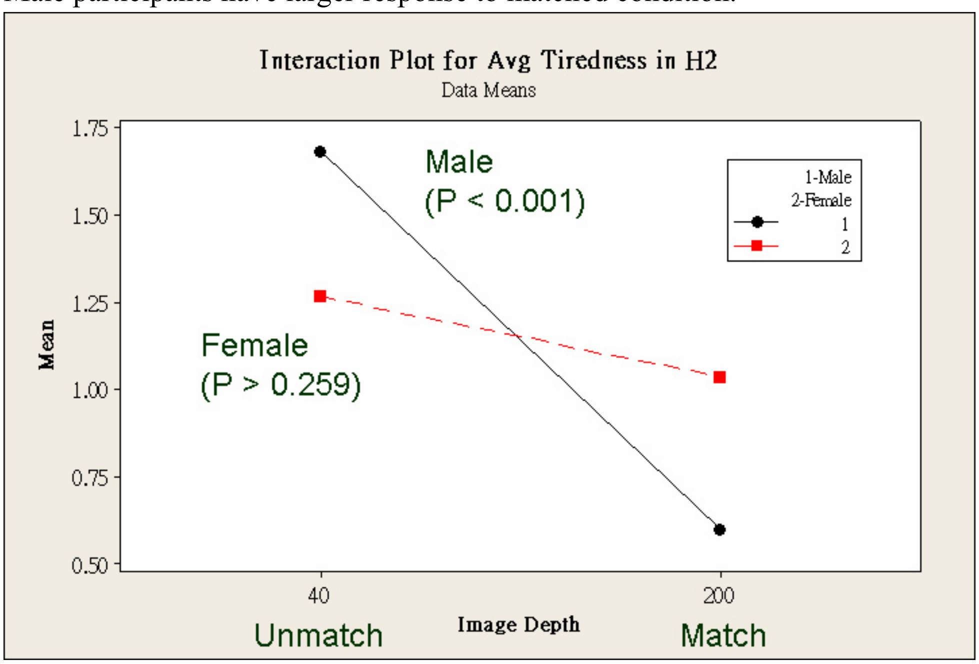

Figure 4.17 Interaction plots for gender and image depth in H2

4.3.3.5 Hypothesis 2: Interaction Effect - Eye sightedness vs Image Depth

Short Sighted participants have larger response to matched condition.

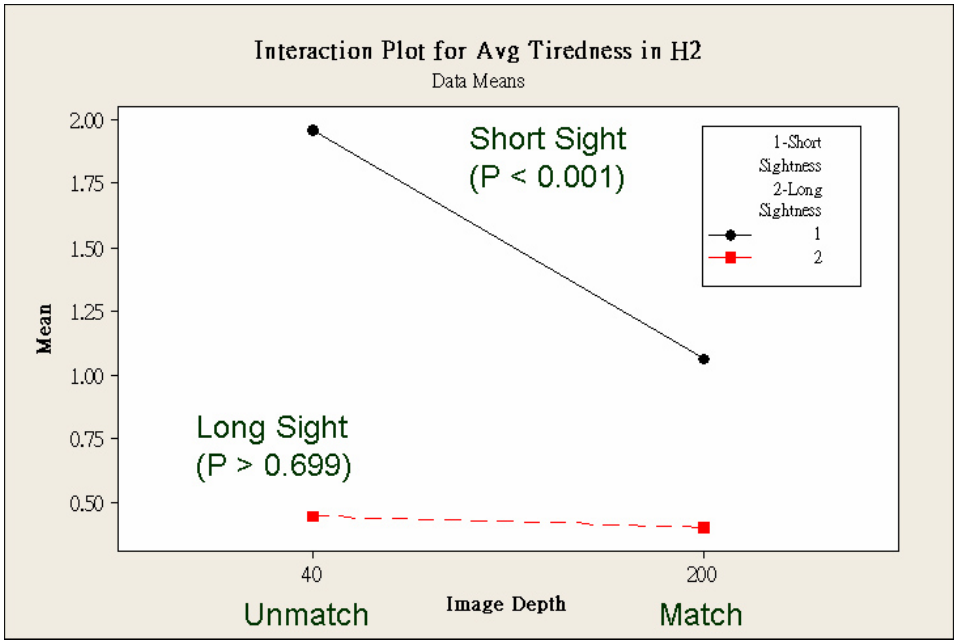

Figure 4.18 Interaction plots for corrected sightedness and image depth in H2

4.3.3.6 Hypothesis 2: Interaction Effect - Eye sightedness vs Gender

Three out of the four male participants are short sighted. Three out of the five female participants are short sighted.

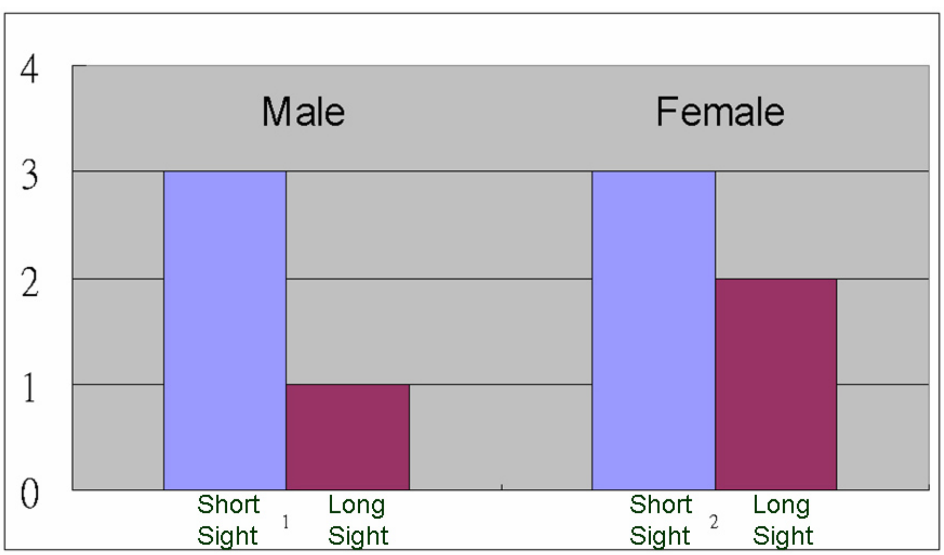

Figure 4.19 Summary of sight status and gender of the participants

4.3.3.7 Summary of the hypotheses 2 (lens focus = 200cm)

From the result H2 is support. (P<0.001). It is an important founding that lens focus at 200cm is commonly used in wearable industry, which mean unmatched condition will lead to higher tiredness in wearable display. At the same time, short sightedness is very common in HK and result shows that it is significantly react with the tiredness. Male participants enjoy more benefit of reduction of tiredness rate in matched condition.

Further ANOVA shows that H2 is support for Male (P < 0.001) and not support for Female. (P > 0.259). H2 is support for short sightedness (P < 0.001) and H2 is not support for long sightedness (P > 0.699). The ANOVA results are shown in Figure 4.20, Figure 4.21, Figure 4.22 and Figure 4.23.

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Imagedepth	1	33.00781250	33.00781250	24.36	<.0001
Duration	15	57.99218750	3.86614583	2.85	0.0013
Sight	1	48.87760417	48.87760417	36.07	<.0001
Imagedepth*Duration	15	11.11718750	0.74114583	0.55	0.9053
Imagedepth*Sight	1	11.00260417	11.00260417	8.12	0.0056
Duration*Sight	15	19.33072917	1.28871528	0.95	0.5133

Figure 4.20 ANOVA for male participant in H2

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Imagedepth	1	1.40625000	1.40625000	1.29	0.2594
Duration	15	74.29375000	4.95291667	4.53	<.0001
Sight	1	26.66666667	26.66666667	24.37	<.0001
Imagedepth*Duration	15	1.89375000	0.12625000	0.12	1.0000
Imagedepth*Sight	1	0.41666667	0.41666667	0.38	0.5384
Duration*Sight	15	9.46666667	0.63111111	0.58	0.8872

Figure 4.21 ANOVA for female participant in H2

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Imagedepth	1	31.6875000	31.6875000	21.10	<.0001
Gender	1	0.0000000	0.0000000	0.00	1.0000
Duration	15	146.4791667	9.7652778	6.50	<.0001
Imagedepth*Gender	1	14.0833333	14.0833333	9.38	0.0026
Imagedepth*Duration	15	11.8125000	0.7875000	0.52	0.9238
Gender*Duration	15	2.1666667	0.1444444	0.10	1.0000

Figure 4.22 ANOVA for participant with corrected short sightedness in H2

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Imagedepth	1	0.04166667	0.04166667	0.15	0.6994
Gender	1	7.52083333	7.52083333	27.23	<.0001
Duration	15	8.29166667	0.55277778	2.00	0.0359
Imagedepth*Gender	1	0.02083333	0.02083333	0.08	0.7848
Imagedepth*Duration	15	1.95833333	0.13055556	0.47	0.9428
Gender*Duration	15	4.14583333	0.27638889	1.00	0.4703

Figure 4.23 ANOVA for participant with corrected long sightedness in H2

4.3.4 Hypothesis 4 (Image Depth = 200cm) : ANOVA

From the ANOVA result, we can found that the main effects: lens focus, duration and sightedness are statistically significant with P<0.001. Gender is not significant. There are three two-way interactions effects: Lens focus with Gender and Gender with Sightedness.

Dependent Variable: Tire

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	66	344.9767361	5.2269202	4.30	<.0001
Error	221	268.7420139	1.2160272		
Corrected Total	287	613.7187500			

R-Square	Coeff Var	Root MSE	Tire Mean
0.562109	92.05450	1.102736	1.197917

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Lensfocus	1	44.3368056	44.3368056	36.46	<.0001
Gender	1	2.6265625	2.6265625	2.16	0.1431
Duration	15	158.6631944	10.5775463	8.70	<.0001
Sight	1	49.0000000	49.0000000	40.30	<.0001
Lensfocus*Gender	1	28.1960069	28.1960069	23.19	<.0001
Lensfocus*Duration	15	12.4965278	0.8331019	0.69	0.7980
Lensfocus*Sight	1	3.3611111	3.3611111	2.76	0.0978
Gender*Duration	15	0.9039931	0.0602662	0.05	1.0000
Gender*Sight	1	27.5036458	27.5036458	22.62	<.0001
Duration*Sight	15	17.8888889	1.1925926	0.98	0.4765

Figure 4.24 ANOVA result of hypothesis 4 (image depth = 200cm). The main effects: lens focus, duration and sightedness are statistically significant with P<0.001. Gender is not significant.

4.3.4.1 Hypothesis 4: Main Effect – Lens Focus

Wilcoxon two-sample tests are done for each main effect as the data is not normalized. The result in Figure 4.25 shows that lens focus is statistically significant in H4 which is consistence with the ANOVA result.

```
Wilcoxon Two-Sample Test

Statistic               17971.5000

Normal Approximation
Z                         -4.2455
One-Sided Pr <  Z          <.0001
Two-Sided Pr > |Z|         <.0001

t Approximation
One-Sided Pr <  Z          <.0001
Two-Sided Pr > |Z|         <.0001

Z includes a continuity correction of 0.5.
```

Figure 4.25 Wilcoxon Two-Sample Test for Lens focus, result shows that image depth is statistically significant in H4.

4.3.4.2 Hypothesis 4: Main Effect – Duration

Figure 4.26 show that the tiredness rating of the matched condition is always lower than the unmatched one when time goes on.

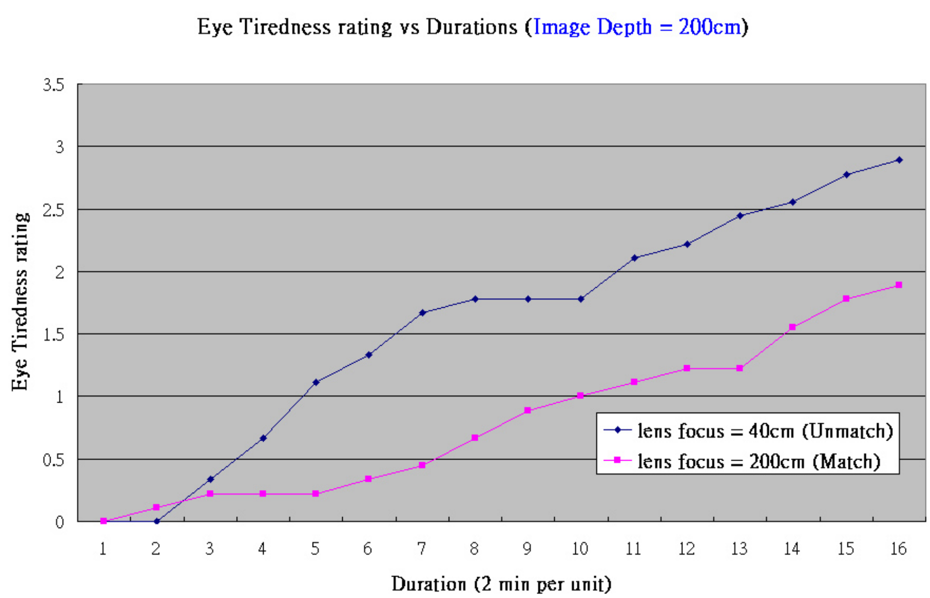

Figure 4.26 Average tiredness rating verse duration for different condition in H4

4.3.4.3 Hypothesis 4: Main Effect – Corrected Eye Sightedness

Wilcoxon two-sample tests are done for each main effect as the data is not normalized. The result in Figure 4.27 shows that corrected eye sightedness is statistically significant in H4 which is consistence with the ANOVA result. Participant with short sightedness are easier to get tired than the participants with long sightedness.

```
          Wilcoxon Two-Sample Test

     Statistic              10634.5000

     Normal Approximation
     Z                         -5.0404
     One-Sided Pr <  Z          <.0001
     Two-Sided Pr > |Z|         <.0001

     t Approximation
     One-Sided Pr <  Z          <.0001
     Two-Sided Pr > |Z|         <.0001

  Z includes a continuity correction of 0.5.
```

Figure 4.27 Wilcoxon Two-Sample Test for corrected eye sightedness, result shows that eye sightedness is statistically significant in H4.

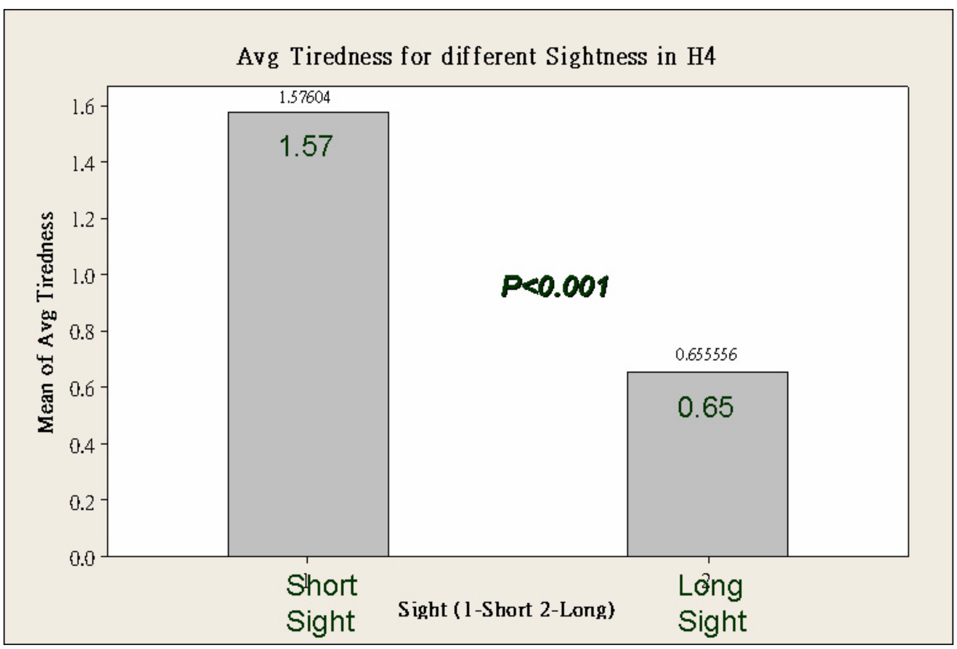

Figure 4.28 Average tiredness of different sighted status in H4

4.3.4.4 Hypothesis 4: Interaction Effect – Gender vs Lens Focus

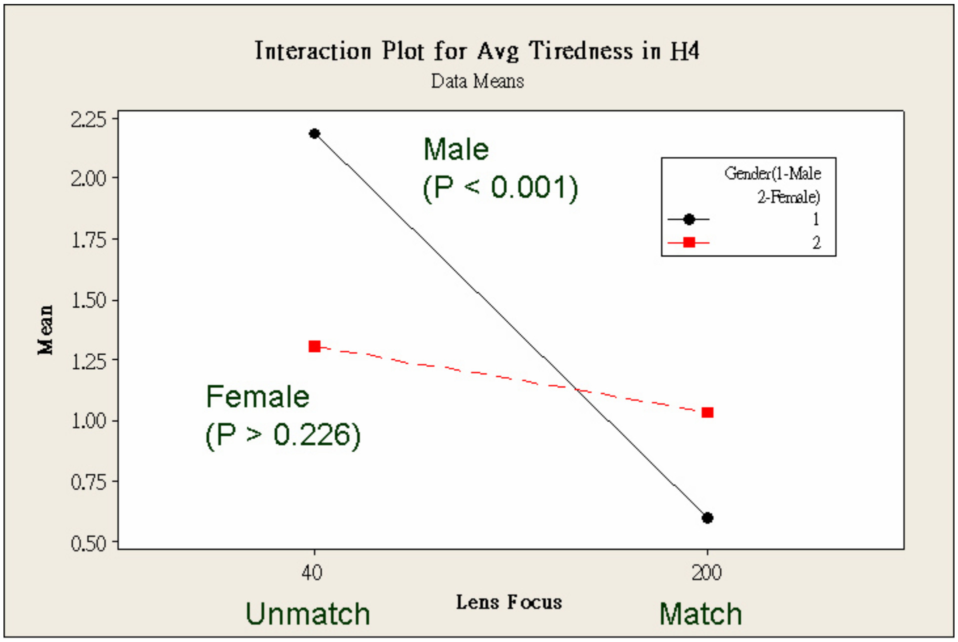

Figure 4.29 Interaction plot for gender and lens focus

4.3.4.5 Hypothesis 4: Interaction Effect – Gender vs Corrected Eye Sightedness

Same as section 4.3.3.6. Please refer to that section for details.

4.3.4.6 Summary of the hypotheses 4 (image depth = 200cm)

From the result, H4 is support (P < 0.001). Further ANOVA shows that H4 is support for Male (P < 0.001) and not support for Female (P > 0.226). H4 is support for Short Sightedness (P < 0.001) and Long Sightedness (P < 0.046). The ANOVA results are shown in Figure 4.30, Figure 4.31,Figure 4.32 and Figure 4.33.

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Lensfocus	1	70.50781250	70.50781250	76.52	<.0001
Duration	15	75.99218750	5.06614583	5.50	<.0001
Sight	1	72.62760417	72.62760417	78.82	<.0001
Lensfocus*Duration	15	16.36718750	1.09114583	1.18	0.3014
Lensfocus*Sight	1	23.50260417	23.50260417	25.51	<.0001
Duration*Sight	15	25.33072917	1.68871528	1.83	0.0442

Figure 4.30 ANOVA for male participant in H4

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Lensfocus	1	2.02500000	2.02500000	1.48	0.2265
Duration	15	83.57500000	5.57166667	4.07	<.0001
Sight	1	3.87604167	3.87604167	2.83	0.0952
Lensfocus*Duration	15	2.77500000	0.18500000	0.14	1.0000
Lensfocus*Sight	1	6.50104167	6.50104167	4.75	0.0314
Duration*Sight	15	3.27395833	0.21826389	0.16	0.9999

Figure 4.31 ANOVA for female participant in H4

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Lensfocus	1	42.1875000	42.1875000	30.43	<.0001
Gender	1	12.0000000	12.0000000	8.66	0.0038
Duration	15	160.6458333	10.7097222	7.73	<.0001
Lensfocus*Gender	1	52.0833333	52.0833333	37.57	<.0001
Lensfocus*Duration	15	11.1458333	0.7430556	0.54	0.9167
Gender*Duration	15	3.6666667	0.2444444	0.18	0.9998

Figure 4.32 ANOVA for participant with corrected short sightedness in H4

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Lensfocus	1	5.51041667	5.51041667	8.88	0.0046
Gender	1	18.13020833	18.13020833	29.22	<.0001
Duration	15	15.90625000	1.06041667	1.71	0.0818
Lensfocus*Gender	1	2.75520833	2.75520833	4.44	0.0405
Lensfocus*Duration	15	5.32291667	0.35486111	0.57	0.8814
Gender*Duration	15	7.95312500	0.53020833	0.85	0.6155

Figure 4.33 ANOVA for participant with corrected long sightedness in H4

4.3.5 Hypothesis 1 (Lens Focus = 40cm) : ANOVA

From the ANOVA result, we can found that the main effects: gender, duration and eye sightedness are statistically significant with $P<0.001$. Image depth is not significant. There are three two-way interactions effects: Image depth with Gender.

Dependent Variable: Tire

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	66	331.8203358	5.0275808	2.32	<.0001
Error	221	479.5928586	2.1701034		
Corrected Total	287	811.4131944			

R-Square	Coeff Var	Root MSE	Tire Mean
0.408941	95.33946	1.473127	1.545139

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Imagedepth	1	0.5868056	0.5868056	0.27	0.6036
Gender	1	12.8444444	12.8444444	5.92	0.0158
Duration	15	225.9954000	15.0663600	6.94	<.0001
Sight	1	77.2934028	77.2934028	35.62	<.0001
Imagedepth*Gender	1	11.2006944	11.2006944	5.16	0.0241
Imagedepth*Duration	15	6.9292213	0.4619481	0.21	0.9993
Imagedepth*Sight	1	0.0017361	0.0017361	0.00	0.9775
Gender*Duration	15	0.0000000	0.0000000	0.00	1.0000
Gender*Sight	1	0.0000000	0.0000000	0.00	1.0000
Duration*Sight	15	0.0000000	0.0000000	0.00	1.0000

Figure 4.34 ANOVA result of hypothesis 1 (lens focus = 40cm). The main effects: gender, duration and sightedness are statistically significant.

4.3.5.1 Hypothesis 1: Main Effect – Gender

Wilcoxon two-sample tests are done for each main effect as the data is not normalized. The result in Figure 4.35 shows that gender is statistically significant in H1 which is consistence with the ANOVA result.

```
Wilcoxon Two-Sample Test

Statistic               19829.5000

Normal Approximation
Z                           1.9691
One-Sided Pr >  Z           0.0245
Two-Sided Pr > |Z|          0.0489

t Approximation
One-Sided Pr >  Z           0.0250
Two-Sided Pr > |Z|          0.0499

Z includes a continuity correction of 0.5.
```

Figure 4.35 Wilcoxon Two-Sample Test for gender, result shows that eye sightedness is statistically significant in H1

4.3.5.2 Hypothesis 1: Main Effect – Duration

Figure 4.36 show that the tiredness rating of the matched condition is similar to the unmatched one when time goes on.

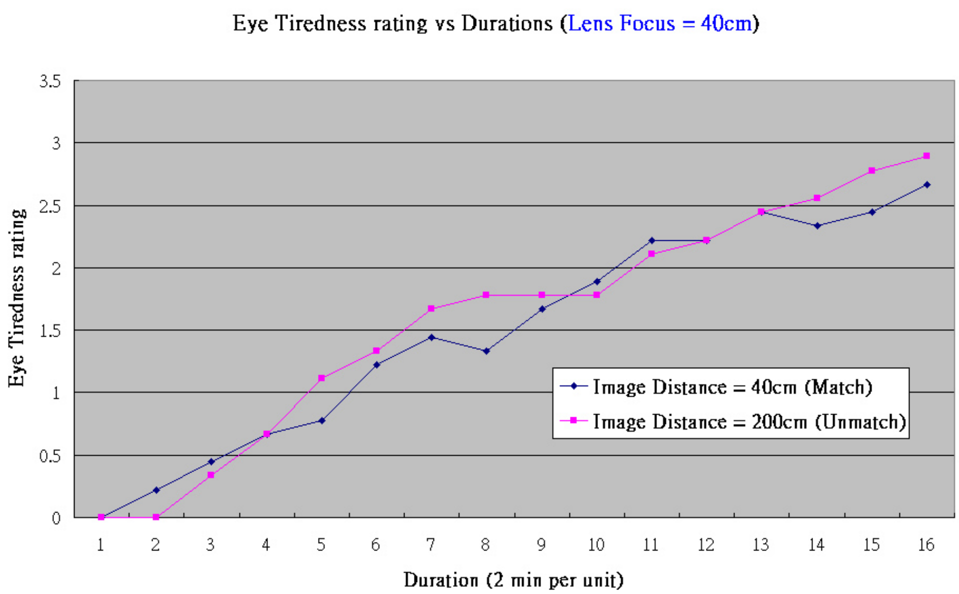

Figure 4.36 Average tiredness rating verse duration for different condition in H1

4.3.5.3 Hypothesis 1: Main Effect – Eye sightedness

Wilcoxon two-sample tests are done for each main effect as the data is not normalized. The result in Figure 4.37 shows that corrected eye sightedness is statistically significant in H1 which is consistence with the ANOVA result. Participant with corrected short sightedness are more easy to get tired than the participants with long sightedness

```
Wilcoxon Two-Sample Test

Statistic              10634.5000

Normal Approximation
Z                         -5.0404
One-Sided Pr <  Z          <.0001
Two-Sided Pr > |Z|         <.0001

t Approximation
One-Sided Pr <  Z          <.0001
Two-Sided Pr > |Z|         <.0001

Z includes a continuity correction of 0.5.
```

Figure 4.37 Wilcoxon Two-Sample Test for corrected eye sightedness, result shows that eye sightedness is statistically significant in H1

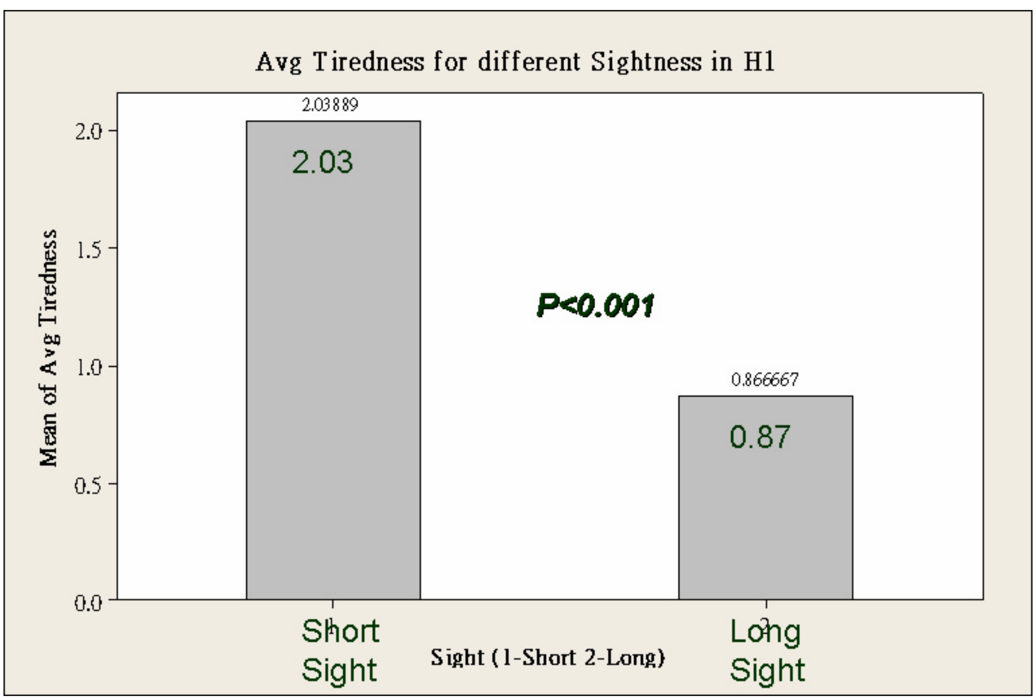

Figure 4.38 Average tiredness of different sighted status in H1

4.3.5.4 Hypothesis 1: Interaction Effect - Eye sightedness vs Image Depth

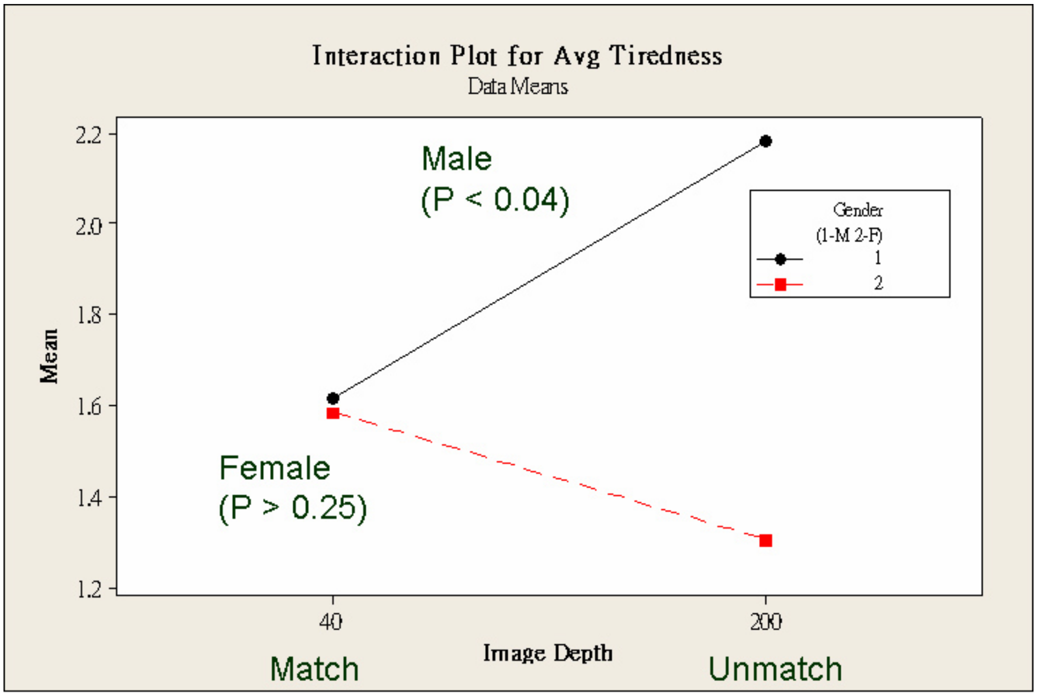

Figure 4.39 Interaction plot for average tiredness for male and female in matched and unmatched condition

4.3.5.5 Summary of the hypotheses 1 (lens focus = 40cm)

From the result, H1 is not support (P > 0.6). Further ANOVA shows that H1 is support for Male (P < 0.001) and not support for Female (P > 0.25). H1 is not support for Short Sightedness (P > 0.6) and Long Sightedness (P > 0.6). The ANOVA results are shown in Figure 4.40, Figure 4.41, Figure 4.42 and Figure 4.43.

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Imagedepth	1	9.0312500	9.0312500	4.24	0.0429
Duration	15	118.5944805	7.9062987	3.71	<.0001
Sight	1	54.0000000	54.0000000	25.33	<.0001
Imagedepth*Duration	15	18.3087933	1.2205862	0.57	0.8874
Imagedepth*Sight	1	36.2604167	36.2604167	17.01	<.0001
Duration*Sight	15	0.0000000	0.0000000	0.00	1.0000

Figure 4.40 ANOVA for male participant in H1

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Imagedepth	1	2.7562500	2.7562500	1.34	0.2501
Duration	15	105.0503157	7.0033544	3.40	<.0001
Sight	1	23.1260417	23.1260417	11.21	0.0011
Imagedepth*Duration	15	3.2705177	0.2180345	0.11	1.0000
Imagedepth*Sight	1	29.0510417	29.0510417	14.09	0.0003
Duration*Sight	15	6.5340593	0.4356040	0.21	0.9993

Figure 4.41 ANOVA for female participant in H1

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Imagedepth	1	0.4218750	0.4218750	0.17	0.6845
Gender	1	11.5052083	11.5052083	4.52	0.0352
Duration	15	186.1903295	12.4126886	4.88	<.0001
Imagedepth*Gender	1	53.1302083	53.1302083	20.87	<.0001
Imagedepth*Duration	15	7.7155237	0.5143682	0.20	0.9995
Gender*Duration	15	0.0000000	0.0000000	0.00	1.0000

Figure 4.42 ANOVA for participant with corrected short sightedness in H1

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Imagedepth	1	0.16666667	0.16666667	0.17	0.6818
Gender	1	1.17187500	1.17187500	1.20	0.2796
Duration	15	39.29166667	2.61944444	2.67	0.0052
Imagedepth*Gender	1	23.38020833	23.38020833	23.87	<.0001
Imagedepth*Duration	15	1.16666667	0.07777778	0.08	1.0000
Gender*Duration	15	1.41145833	0.09409722	0.10	1.0000

Figure 4.43 ANOVA for participant with corrected long sightedness in H1

4.3.6 Hypothesis 3 (image depth = 40cm): ANOVA

From the ANOVA result, we can found that the main effects: duration and eye sightedness are statistically significant with P<0.001. Image depth and gender are not significant. There are no two-way interactions effects.

Dependent Variable: Tire

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	66	321.6012429	4.8727461	2.55	<.0001
Error	221	423.0098682	1.9140718		
Corrected Total	287	744.6111111			

R-Square	Coeff Var	Root MSE	Tire Mean
0.431905	96.71067	1.383500	1.430556

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Lensfocus	1	1.3888889	1.3888889	0.73	0.3952
Gender	1	3.1173611	3.1173611	1.63	0.2032
Duration	15	188.7598899	12.5839927	6.57	<.0001
Sight	1	100.8350694	100.8350694	52.68	<.0001
Lensfocus*Gender	1	2.3361111	2.3361111	1.22	0.2705
Lensfocus*Duration	15	2.2651101	0.1510073	0.08	1.0000
Lensfocus*Sight	1	1.6684028	1.6684028	0.87	0.3515
Gender*Duration	15	3.7676985	0.2511799	0.13	1.0000
Gender*Sight	1	0.0000000	0.0000000	0.00	1.0000
Duration*Sight	15	20.3873639	1.3591576	0.71	0.7732

Figure 4.44 ANOVA result of hypothesis 3 (image depth = 40cm). The main effects: duration and eye sightedness are statistically significant.

4.3.6.1 Hypothesis 3: Main Effect - Duration

Figure 4.45 show that the tiredness rating of the matched condition is similar to the unmatched one when time goes on.

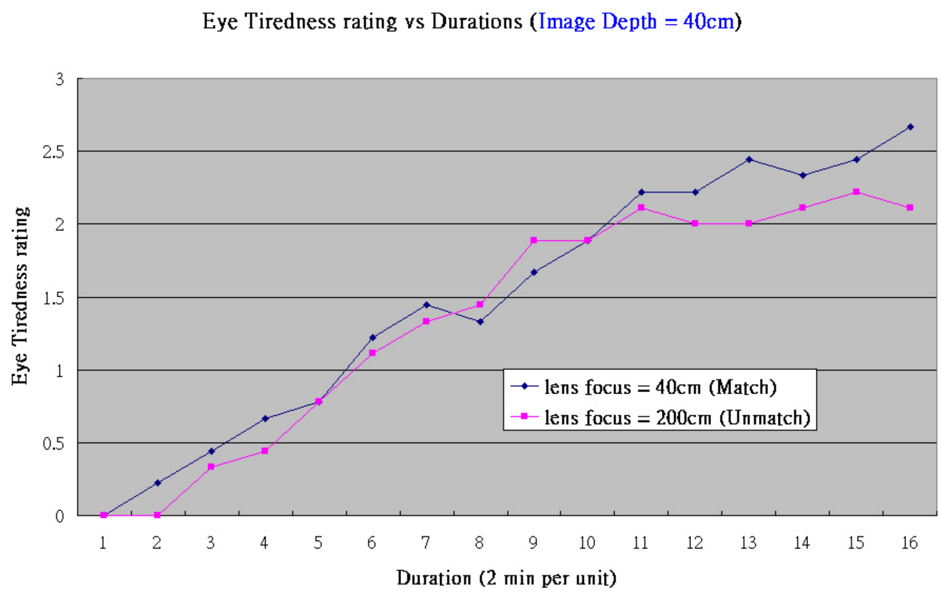

Figure 4.45 Average tiredness rating verse duration for different condition in H3

4.3.6.2 Hypothesis 3: Main Effect – Corrected Sightedness

Wilcoxon two-sample tests are done for each main effect as the data is not normalized. The result in Figure 4.46 shows that corrected eye sightedness is statistically significant in H3 which is consistence with the ANOVA result. Participant with corrected short sightedness are easier to get tired than the participants with long sightedness

```
        Wilcoxon Two-Sample Test

    Statistic              10634.5000

    Normal Approximation
    Z                         -5.0404
    One-Sided Pr <  Z          <.0001
    Two-Sided Pr > |Z|         <.0001

    t Approximation
    One-Sided Pr <  Z          <.0001
    Two-Sided Pr > |Z|         <.0001

Z includes a continuity correction of 0.5.
```

Figure 4.46 Wilcoxon Two-Sample Test for Sightedness in H3

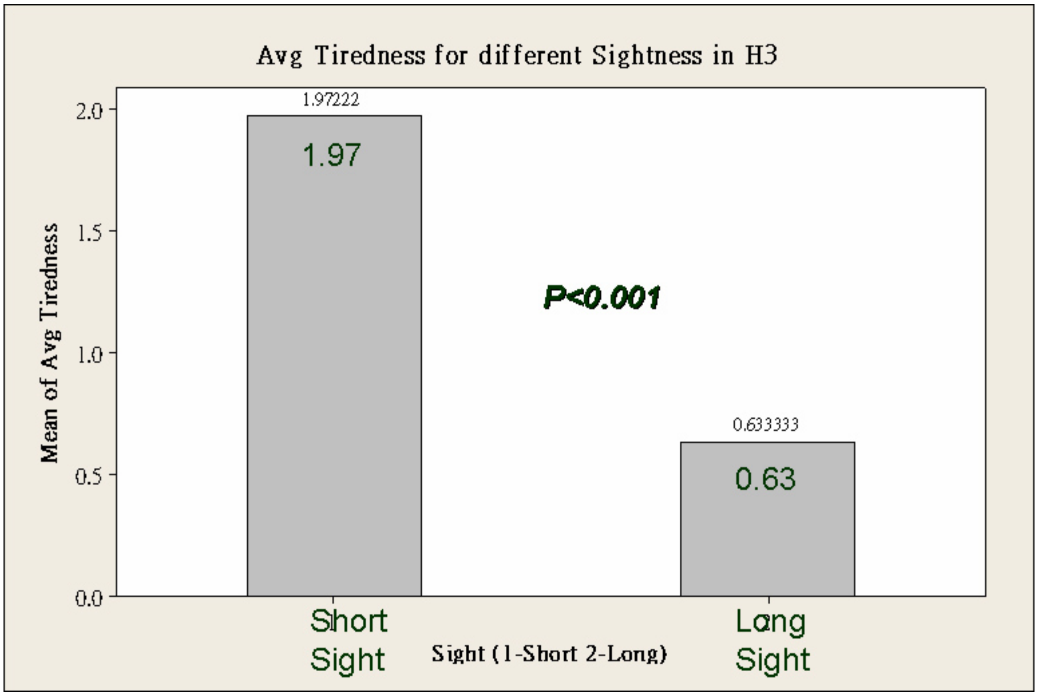

Figure 4.47 Average tiredness of different sighted status in H3

4.3.6.3 Summary of the hypotheses 3 (image depth = 40cm)

From the result, H3 is not support (P > 0.39). Referring to Figure 4.9, it is found that the tiredness rating of the matched condition (1.6) is higher than the unmatched condition (1.45). In the matched condition of H3, eyes are in normal accommodation fashion while converge is not matched. It is the support that accommodation of the eye is another factor that influences the tiredness of eye and it has a greater effect.

Further ANOVA shows that H3 is not support for Male (P > 0.82) and Female (P > 0.16). H1 is not support for Short Sightedness (P > 0.89) and support for Long Sightedness (P < 0.028). The ANOVA results are shown in Figure 4.48, Figure 4.49, Figure 4.50 and Figure 4.51.

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Lensfocus	1	0.12500000	0.12500000	0.05	0.8235
Duration	15	97.46875000	6.49791667	2.60	0.0032
Sight	1	33.84375000	33.84375000	13.55	0.0004
Lensfocus*Duration	15	2.12500000	0.14166667	0.06	1.0000
Lensfocus*Sight	1	20.16666667	20.16666667	8.08	0.0057
Duration*Sight	15	8.73958333	0.58263889	0.23	0.9986

Figure 4.48 ANOVA for male participant in H3

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Lensfocus	1	3.60000000	3.60000000	2.00	0.1601
Duration	15	95.05883838	6.33725589	3.52	<.0001
Sight	1	64.06666667	64.06666667	35.58	<.0001
Lensfocus*Duration	15	2.36616162	0.15774411	0.09	1.0000
Lensfocus*Sight	1	4.81666667	4.81666667	2.68	0.1047
Duration*Sight	15	12.02092352	0.80139490	0.45	0.9615

Figure 4.49 ANOVA for female participant in H3

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Lensfocus	1	0.0468750	0.0468750	0.02	0.8931
Gender	1	0.0052083	0.0052083	0.00	0.9643
Duration	15	182.4910038	12.1660669	4.70	<.0001
Lensfocus*Gender	1	14.6302083	14.6302083	5.65	0.0187
Lensfocus*Duration	15	2.0247700	0.1349847	0.05	1.0000
Gender*Duration	15	3.3283415	0.2218894	0.09	1.0000

Figure 4.50 ANOVA for participant with corrected short sightedness in H3

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Lensfocus	1	3.01041667	3.01041667	5.31	0.0257
Gender	1	0.18750000	0.18750000	0.33	0.5680
Duration	15	26.65625000	1.77708333	3.13	0.0014
Lensfocus*Gender	1	11.02083333	11.02083333	19.44	<.0001
Lensfocus*Duration	15	2.82291667	0.18819444	0.33	0.9886
Gender*Duration	15	0.81250000	0.05416667	0.10	1.0000

Figure 4.51 ANOVA for participant with corrected long sightedness in H3

5 DISCUSSION, CONCLUSION, LIMITATIONS AND FUTURE WORK

5.1 DISCUSSION AND CONCLUSION

In this thesis, we have successfully developed a microdisplay system with computer-controlled dynamically adjustable lens focus. Results of two experiments show that matching lens focus and stereoscopic depth cues of the displayed images can reduce the occurrence of double images as well as reduce levels of eye fatigue of the users. Detailed findings are summarized below.

Major finding 1: Single image formation time is significantly reduced when lens focus is matched with the stereoscopic depth cues of the images. This is the main finding of the preliminary experiment (see Chapter 3). In the main effect plot of lens focus and the ANOVA result of the preliminary experiment, it was clearly shown that matching the stereo depth of displayed images and the lens focus could significantly reduce the time required to form a single stereo image from a binocular vision. This finding is important because it demonstrates task performance benefits as a result of adjusting the lens focus appropriately.

Major finding 2: For a binocular display with lens focus set at 200cm, viewing images with stereoscopic depth appropriate to the lens focus will result in significantly lower rated eye tiredness ratings. This is the main finding of the main experiment (see Chapter 4). This is an important finding as fixed lens focus at 200cm is commonly used among commercially available wearable displays. The author has been working in the micro-display industry for five years and the most frequent complains from the clients are the eye strain. This current finding could explain, at least partially, the cause of the eye fatigue problems.

Base upon the current findings, the author recommends the wearable binocular displays manufactures to design an automatic lens focus system for wearable displays. Several technologies to dynamically adjust the lens focus are emerging (e.g., tunable liquid micro-lens system: Moench and Zappe (2005) [29] and stacked LCD lattice from 3-Deep, 2005 [30]) and the author expects the cost of implementing an adjustable lens focus solution will come down rapidly in the near future.

Side Findings

Results show that viewers with corrected short-sightedness have significant higher rated eye fatigue ratings than their counter-part with corrected long-sightedness. Also, the group of viewers with corrected short-sightedness have the largest significant benefits from matching lens focus with the stereoscopic depth cues. This is of particular importance to Hong Kong because about 87% of people in Hong Kong are short-sighted (Ting et al., 2004 [31]). It is an interesting side observation that male participants in general completed the visual tasks faster than their female counter-parts. This observation may explain the side-finding that male participants have significantly higher rated eye fatigue ratings than female participants. In turn, this may explain why male participants seemed to have benefited from appropriately adjusted lens focus to a larger extend then female participants.

5.2 LIMITATIONS AND FUTURE WORK

In this study, only the full fractorial combinations of 40cm and 200cm lens focus and stereoscopic depth cues appropriate to an image depth of 40cm and 200cm have been studied in the main experiment. In particular, the displayed images used had been stationary, future studies using images of varying depth cues should be conducted.

Based on the results of the main experiment, we recommend that manufacturers of wearable displays consider creating an auto-adjustable lens focus sytem to reduce occular tiredness among users.

In the main experiment, it has been observed that viewing images at a lens focus of 40cm may cause eye fatigue regardless of whether the lens focus is matched with the stereoscopic cues or not. Future work to study the interactions effects of accommodation and effects of matching lens focus with stereo depth cues are needed.

Although effects concerning the higher eye fatigue associated with participants with corrected short sightedness are statistically significant, the samples size is not large. Further studies with more participants are needed to confirm the finding.

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6 APPENDIX

6.1 Report of Lens focus verification of the equipment

Abstract

In last experiment, it was assumed that the cameras' focus marks were accurately representing the actual distance between focused object and the camera. It is not necessarily correct and should be verified. This experiment aims to find the relationship between the camera focus mark actual distance between focused object and the camera, so as to conclude the validity of the results obtained by the cameras.

From the experimental results, the focus marks of Olympus camera are not accurate. Instrumental error at the camera focus range is found. On the other hand, the focus marks of Minolta camera are accurate. For the Panasonic camera, the result shows that the infinity position of the camera focus is not at the end-stop. The deviation between the corresponding image focus distance and the physical distance is high (1.024m compares with 20m; 5.292m compares with 40-50m).

Based on the results, only the Minolta camera is reliable in the aspect of instrument accuracy. In the last experiment, only the experimental results using Minolta camera is valid. In last experiment, the most important finding is the trend of "the larger the image focal distance, the larger the camera focus distance" is observed. Because the Minolta camera focus marks are accurate, the trend of "the larger the image focal distance, the larger the camera focus distance" is confirmed.

Nevertheless the experimental results using Olympus camera and Panasonic camera still provide information by the trend of the focus distance change. If the error pattern of the Olympus camera is clarified, the experimental results using Olympics camera in the last experiment can become valuable. But as long as there is one set of valid data (by Minolta camera), the case of Olympus camera can be put aside as it is not the main concern. The design of auto focus system can be primary verified by the results using Minolta camera. The design will be further secured by the confirmation of lens focus length from the lens manufacturer, and a more precise experiment using optical instruments.

Introduction

The observation of last experiment is repeated here.

Trial	d (mm)	image seen by human eye	Image captured by Panasonic camera	Image captured by Olympus camera	image captured by Minolta camera
1	23.08	sharp	sharp when camera focus sets to **2 and 11/12 turns from infinity (around 30cm)**	seems sharper when camera focus sets to **35cm**	seems sharper when camera focus sets to **near most (i.e. 0.5m)**

2	23.58	sharp; no detectable change to d=23.08	sharp when camera focus sets to **2 and 9/12 turns from infinity (around 40cm)**	seems sharper when camera focus sets to **40 - 60cm**	seems sharper when camera focus sets to **the side of 0.5m)**
3	24.08	sharp; no detectable change to d=23.58	sharp when camera focus sets to **2 and 8/12 turns from infinity (around 40-50cm)**	seems sharper when camera focus sets to **60cm**	seems sharper when camera focus sets to **80cm)**
4	24.58	sharp; no detectable change to d=24.08	sharp when camera focus sets to **2 and 6/12 turns from infinity**	seems sharper when camera focus sets to **2m - 5m**	seems sharper when camera focus sets to **2m and more**
5	25.08	Blur detectable	sharp when camera focus sets to **2 and 4/12 turns from infinity**	seems sharper when camera focus sets to **around 5m**	seems sharper when camera focus sets to **2m and more**
6	25.58	blurry; more blurry to d=25.08	sharp when camera focus sets to **2 and 3/12 turns from infinity**	seems sharper when camera focus sets to **Infinity**	seems sharper when camera focus sets to **Infinity**
7	26.08	blurry; more blurry to d=25.58	sharp when camera focus sets to **2 and 1.5/12 turns from infinity**	seems sharper when camera focus sets to **Infinity, but cannot find focused image by whole range of camera**	seems sharper when camera focus sets to **Infinity, but cannot find focused image by whole range of camera**
8	26.58	blurry	sharp when camera focus sets to **2 and 1/12 turns from infinity**	**cannot find focused image by whole range of camera**	**cannot find focused image by whole range of camera**
9	27.08	blurry	sharp when camera focus sets to **2 turns from infinity**	**cannot find focused image by whole range of camera**	**cannot find focused image by whole range of camera**
10	41 (approx.)	blurry	sharp when camera focus sets to **0 turn from infinity**	**cannot find focused image by whole range of camera**	**cannot find focused image by whole range of camera**

The result of Olympus and Minolta cameras of last experiment is quantified and presented here.

Trial	d (mm)	Corresponding image focus distance (meter); Calculated using lens focal length = 25.2mm (*)	focal distance of image captured by Olympus camera (meter)	focal distance of image captured by Minolta camera (meter)
1	23.08	0.300	0.35	0.5

2	23.58	0.392	0.5	0.5
3	24.08	0.567	0.6	0.8
4	24.58	1.024	3.5 (***)	2 (****)
5	25.08	5.292	5	2 (*****)
6	25.58	-1.671	infinity	infinity
7	26.08	-0.722	out-focus	out-focus
8	26.58	-0.460	out-focus	out-focus
9	27.08	-0.338	out-focus	out-focus

(**)

Remark:

(*) The focal length 25.2mm is an estimated figure. The exact figure is subject to answer of lens manufacturer which is on wait now.

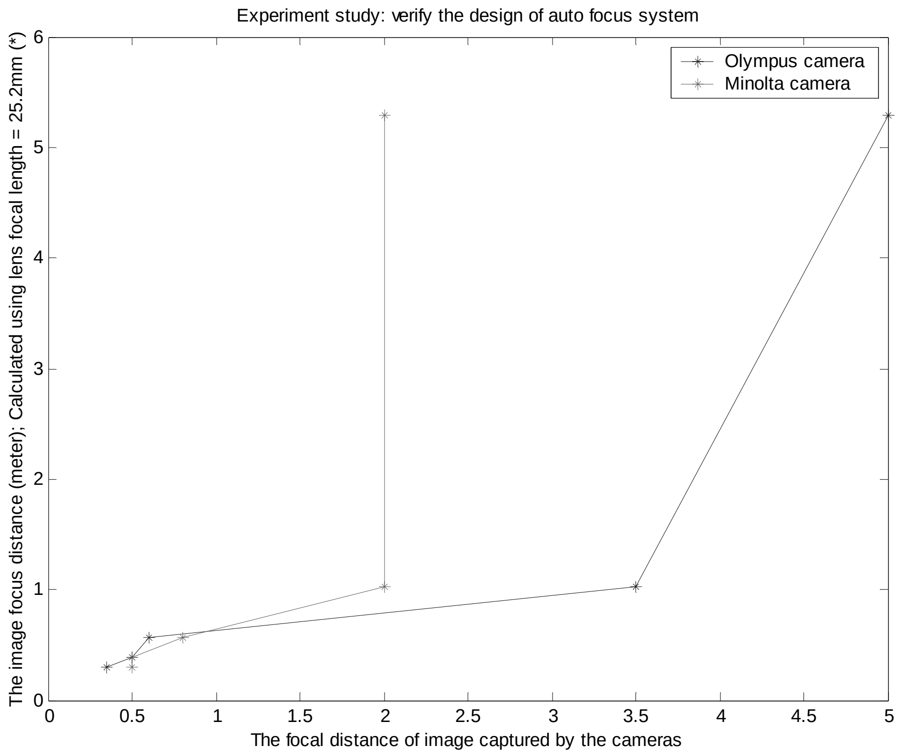
(**) In theory, the negative value of d means the image is real. In this case, the negativity may be contributed by the uncertain value of the focal length. This can be clarified when the exact focal length value is known.

(***) The value of 3.5 comes from (2+5)/2, which is based on the observation "seems sharper when camera focus sets to 2m - 5m".

(****) The value of 2 is based on the observation "seems sharper when camera focus sets to 2m and more".

(*****)The value of 2 is based on the observation "seems sharper when camera focus sets to 2m and more".

The result of last experiment is presented here graphically. Data of d=infinity is not plotted. The non-linear relationship in the graph is due to the camera focus marks is not very fine. In last experiment, the most important finding is the trend of "the larger the image focal distance, the larger the camera focus distance" is observed.



Objective of Experiment

In last experiment, it was assumed that the cameras' focus marks were accurately representing the actual distance between focused object and the camera. It is not necessarily correct and should be verified.

In particular, the Panasonic camera does not have any focus mark on it. It only indicates the direction to near and infinity.

This experiment aims to find the relationship between the camera focus mark actual distance between focused object and the camera, so as to conclude the validity of the results obtained by the cameras.

Experiment Design

In general, the cameras focus will set to a particular position according to the focus marks of the camera. Then the camera will point to a target object, and alter the camera position until it captures a sharp image of the target object (i.e. the target object is focused). After that, the physical distance between the object and the camera is measured. The measured distance and the camera focus distance will be compared. In ideal case, the measured distance and the camera focus distance are the same. This implies the camera focus distance is correct and accurate.

Camera

The cameras are:

- Panasonic GP-LM7TA camera, with manual focus ranges from near to infinity
- Olympus Camedia C2020 Z digital camera, with manual focus ranges from 20cm to infinity.
- Minolta X-300 film camera, with manual focus ranges from 0.5m to infinity.

Panasonic Camera

As the Panasonic camera does not have any focus mark on it (only indicates the direction to near and infinity), the general experiment will not conduct on this camera.

According to this special condition, alternative experiment will be conducted on this camera. The camera will point to an object with known distance. The camera focus is altered until the object is focused. The Panasonic camera is linked to a CRT monitor. The experimenter can see the image captured at the monitor and determine the sharpness of the image. The camera focus position will be recorded and then be compared with previous experimental result.

Olympus Camera

The Olympus camera has several marks on the focus range: 20cm, 40cm, 60cm, 80cm, 2m, 3m, 5m, and infinity.

The Olympus camera has a digital LCD view finder. The experimenter can see the image captured at the monitor and determine the sharpness of the image. But the resolution of the view finder would be not high enough for easy judgment. In some certain cases, the experimenter will set the camera focus and then take photos of the image at different distance between object and camera, and judge the sharpness of image in different photos.

Minolta Camera

The Minolta camera has an optical view finder. It is easier than at the Olympus camera to judge the image sharpness of the target object. It is anticipated that the human error involved in the measurement is much less than at the Olympus camera.

The Minolta camera has several marks on the focus range: 50cm, 55cm, 60cm, 70cm, 80cm, 90cm, 1m, 1.2m, 1.5m, 2m, 3m, 5m, 10m, and infinity.

Result and Analysis

Panasonic Camera

Experiment conducted on two distant objects.

When the Panasonic camera focuses to an object about 20m away, the camera focus set to 2 and 6/12 turns from the end-stop.

When the Panasonic camera focuses to an object about 40-50m away, the camera focus set to 2 and 4/12 turns from the end-stop.

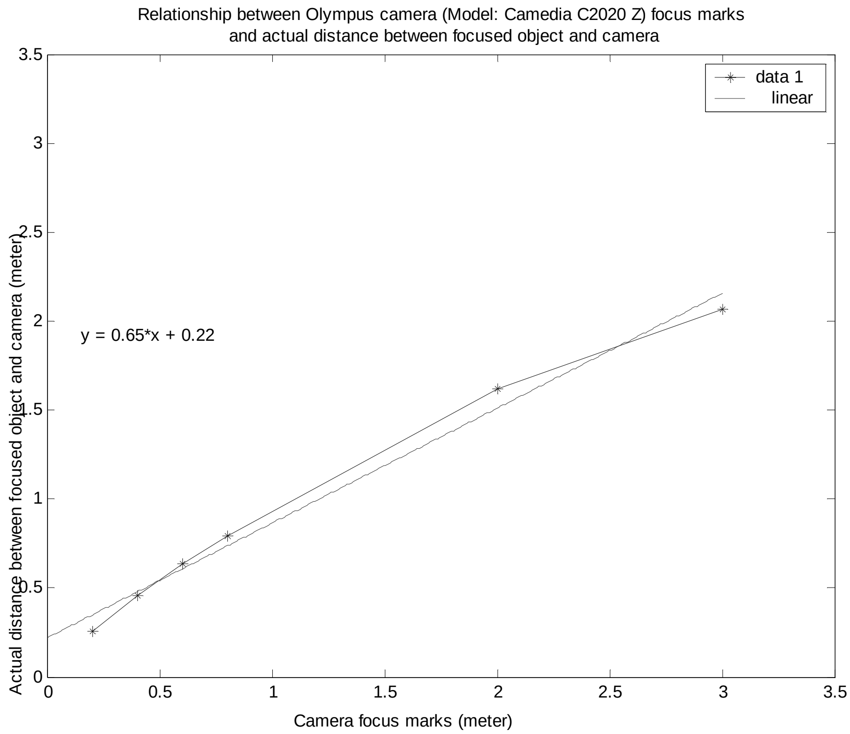
The result shows that the infinity position of the camera focus is not at the end-stop.
Refer to the previous experiment, when camera focus set to 2 and 6/12 turns from the end-stop, d = 24.58mm i.e. Corresponding image focus distance = 1.024m. When camera focus set to 2 and 4/12 turns from the end-stop, d = 25.08mm i.e. Corresponding image focus distance = 5.292m.

The deviation between the corresponding image focus distance and the physical distance is high (1.024m compares with 20m; 5.292m compares with 40-50m).

Olympus camera

The deviation between the camera focus marks and the physical distance is high.

Olympus camera focus mark (m)	physical distance (roughly) between focused object and camera CCD (m)
0.2	0.255
0.4	0.46
0.6	0.636
0.8	0.793
2	1.62
3	2.07
5	-
infinity	far away



Remark: the point of infinity is not plotted.

It can be seen that deviation is more obvious when focus marks are 2m, 3m and onwards.

For focus mark = 5m, it is too difficult to determine the image sharpness from the LCD viewfinder. At this case, some photos are taken at different physical distance to see their sharpness.

		
Camera focus 5m; physical distance 2m.	Camera focus 5m; physical distance 4m.	Camera focus 5m; physical distance 5m.

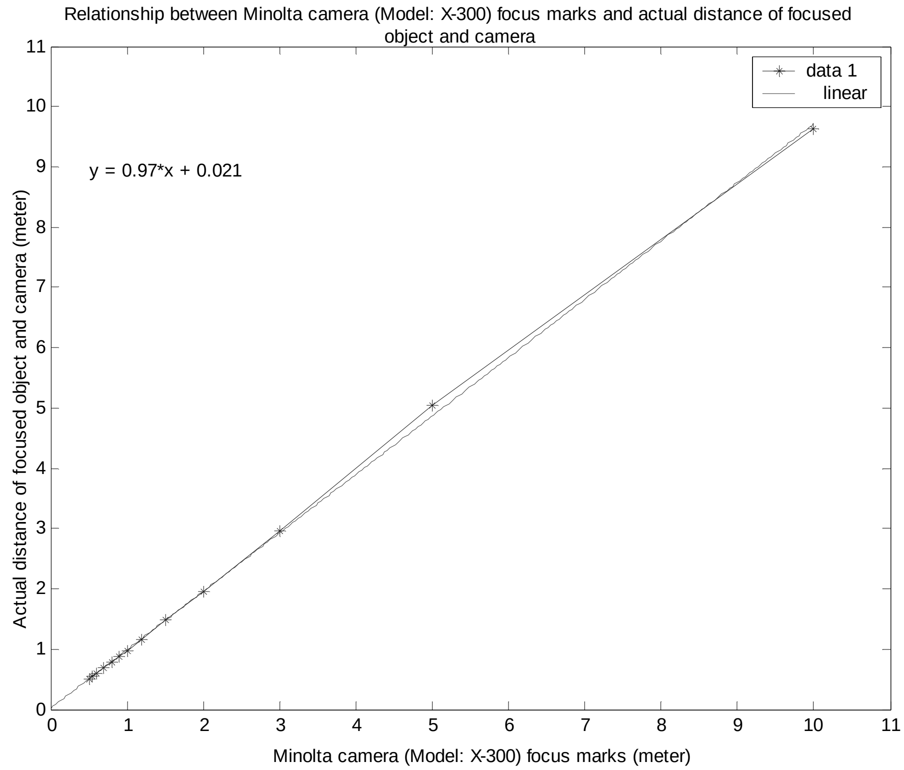
It is found that the sharpest photo is the one that physical distance 2m. The photos that physical distance 4m and physical distance 5m have some degree of out-focus.

From the results, the focus marks of Olympus camera are not accurate. The low accuracy of Olympus camera focus marks is not only due to human error i.e. the difficulty of determine the image sharpness. The results shows when the camera focus is set to 5m, the sharpest photo is the one that physical distance 2m. The photos that physical distance 4m and physical distance 5m have some degree of out-focus. This obviously indicates the camera focus range has deviated from the physical focus distance. This is an instrumental error.

Minolta camera

The deviation between the camera focus marks and the physical distance is small.

Minolta camera focus mark (m)	actual distance between focused object and camera film position (m)
0.5	0.495
0.55	0.552
0.6	0.59
0.7	0.687
0.8	0.792
0.9	0.885
1	0.966
1.2	1.152
1.5	1.476
2	1.943
3	2.957
5	5.045
10	9.628
infinity	far away



Remark: the point of infinity is not plotted.

From the results, the focus marks of Minolta camera are accurate.

Conclusion

From the experimental results, the focus marks of Olympus camera are not accurate. Instrumental error is found. On the other hand, the focus marks of Minolta camera are accurate.

For the Panasonic camera, the result shows that the infinity position of the camera focus is not at the end-stop. The deviation between the corresponding image focus distance and the physical distance is high (1.024m compares with 20m; 5.292m compares with 40-50m).

Based on the results, only the Minolta camera is reliable in the aspect of instrument accuracy. In the last experiment, only the experimental results using Minolta camera is valid. In last experiment, the most important finding is the trend of “the larger the image focal distance, the larger the camera focus distance” is observed. Because the Minolta camera focus marks are accurate, the trend of “the larger the image focal distance, the larger the camera focus distance” is confirmed.

Nevertheless the experimental results using Olympus camera and Panasonic camera still provide information by the trend of the focus distance change.

If the error pattern of the Olympus camera is clarified, the experimental results using Olympics camera in the last experiment can become valuable. But as long as there is one set of valid data (by Minolta camera), the case of Olympus camera can be put aside as it is not the main concern.

The design of auto focus system can be primary verified by the results using Minolta camera. The design will be further secured by the confirmation of lens focus length from the lens manufacturer, and a more precise experiment using optical instruments.

6.2 Glossary of Terms

6.2.1 Terms related to optometry

Vergence- to turn the eyes horizontally (convergence- inward or divergence- outward). Accommodative vergence, fusional vergence, proximal vergence, and tonic vergence are needed to maintain single vision.

Convergence- the ability to use both eyes as a team and to be able to turn the eyes inward to maintain single vision up close**.**

Diopter (D) - a measurement of the refractive (light bending) power of a lens or a prism (pd). The strength of prescription glasses and contacts are measured in these units. For example a lens that is 0.50 diopter (D) is very weak, where as a lens that is 10.0 diopter (D) is very strong.

Divergenc*e*- the ability to use both eyes as a team and be able to turn the eyes out toward a far object.

Near Acuity- the eye's ability to distinguish an object's shape and details at a near distance such as 16 inches (40 cm).

Proximal Vergence- a convergence response attributed to the awareness of, or the impression of nearness of an object of regard.

Pupillary Distance (PD*)*- the distances between the pupils of the eyes, in millimeters -- a necessary measurement for proper lens prescription.

Pupillometer- a device used to measure the distance between the pupils of the eyes, in millimeters, which is a necessary measurement for proper lens prescription. It also measures the diameter of the pupil.

Retinoscopy- this technique determines the eye's refractive error and the best corrective lenses to be prescribed. An instrument called a retinoscope which consists of a light, lens, mirror, and handle, is used to shine light into a patient’s eye.

Stereopsis- the ability to perceive a three dimensional depth which requires adequate fusion (union) of the images from each eye.

Stereopsis Test- measures depth perception that is dependent on the accuracy of eye teaming.

Tonic Vergence- convergence due to the basic tonicity (tension) of the extraocular muscles, which are responsible, in part, for the distance phoria. Deficient tonic vergence would result in exophoria and excessive tonic vergence results in esophoria.

Visual Acuity- sharpness or clearness of eyesight. For more information, please click here. (See "Near Acuity" and "Distance Acuity", “20/20”)

20/20 -the expression for normal eyesight (or 6/6 in countries where metric measurements are used). This notation is expressed as a fraction. The numerator (1st number) refers to the distance you were from the test chart, which is usually 20 feet (6 meters). The denominator (2nd number) denotes the distance at which a person with normal eyesight could read the line with the smallest letters that you could correctly read. For example, if your visual acuity is 20/100 that means that the line you correctly read at 20 feet could be read by a person with normal vision at 100 feet.

Accommodation- (eye focusing) the eye's ability to adjust its focus by the action of the ciliary muscle, which increases the lens focusing power. When this accommodation skill is working properly, the eye can focus and refocus quickly and effortlessly, which is similar to an automatic focus feature on a camera.

6.2.2 Terms related to sterescopic vision

Binocular images - A pair of left and right images which the content on the left image has a horizontal position difference from the content on the right image.

Biocular images- A pair of left and right images which the content on the left image is identical to the content on the right image.

Asthenopia - eyestrain, symptoms include excessive tearing, itching, burning, visual fatigue, and headache. It can be caused from an uncorrected refractive error, accommodation (eye focusing) disorder, binocularity (eye teaming) disorder, or by extended, intense use of the eyes.

Eye relief - The distance between the last surface of the lens of the micro-display system and the position of the exit pupil. If the eyes are located within the eye relief (i.e. located between the lens and the position of the exit pupil), the whole display can be viewed.

Focal length of lens - The distance between the lens and the focal point. Taking the convergent magnifying lens of the micro-display system as an example, if parallel light rays pass through the lens, the light rays will be refracted and pass the focal point. The focal length is determined by the radii of curvature of the lens surface and the refractive index of the lens material.

Image distance- In a micro-display system, image distance is the distance between the magnified virtual image and the lens. Inter-ocular distance (IOD) The inter-distance between the centre of the left and right lens of the micro-display system.

Lens focus - In a micro-display system, lens focus is the distance between the magnified virtual image and the principle plane of the lens. Lens focus shares the same meaning as image distance.

Lens formula - Describes the relationship between lens focus, object distance and focal length of the lens. The formula is $1/u = 1/v + 1/f$
Where v = image distance, u = object distance, f = focal length of the lens.

Object depth - The virtual depth of the object in the virtual environment. It is determined geometrically by the stereoscopic depth cues (i.e. the horizontal position difference of the objects on the respective left and right binocular images).

Object distance- In a micro-display system, object distance is the distance between the micro-display screen and the magnifying lens.

Stereoscopic images - A pair of left and right binocular images where the objects on the left and right images have different extents of horizontal position difference. The images carry depth information and allow the viewers to perceive the depth of the objects.

Stereoscopic depth cues - The horizontal position difference of the objects on a pair of left and right binocular images.

Inter-pupillary distance (IPD) - The inter-distance between the centre of the left and right pupils of the eyes.

Refractive error in bright condition = SPH + CYL/2 (SPH and CYL are measured in bright condition. i.e. room light was turned on) only one data was obtained

Pre-exposure dark focus = Refractive error in bright condition - Pre-exposure refractive error in complete darkness

Post-exposure refractive error in complete darkness = SPH + CYL/2
(SPH and CYL are measured in complete darkness after seeing micro-display for 30 mins) every 30 seconds take one data, measurement last for 5 mins, so 10 data was obtained.

Post-exposure dark focus = Refractive error in bright condition - Post-exposure refractive error in complete darkness (so we have 10 data on Post-exposure dark focus)

Change in dark focus = Post-exposure dark focus – (the average of last 4 data on

Pre-exposure dark focus) (so we have 10 data on Change in dark focus)

6.2.3 Terms in the experiment task

Single image (formed by viewer) -this term is referred to as the single image perceived by the viewers when they obtain single vision at a pair of biocular images.

Double images (formed by viewer) - this term is referred to as the images perceived by the viewers beforethey obtain single vision at either a pair of biocular images or binocular images.

6.3 Reference of the preliminary experiment

6.3.1 Preliminary experiment procedure

Procedure for the Experiment of Micro-display

A concise list of procedures for the experimenter.

1. Preparation

1.1. Consent

1.1.1. Explain the purpose of the experiment to the subject.

1.1.2. Subject is require to fill in a Subject Information Sheet*.

1.1.3. Subject is require to read and sign Consent Form.

1.2. Calm down

1.2.1. Remind the subject if he/she needs to go to toilet.

1.2.2. Remind the subject to drink only a little.

1.2.3. Remind the subject to turn off telephone.

1.2.4. Ask the subject take some rest to calm down.

1.2.5. Open task 1.

1.3. Calibration

1.3.1. Measure the subject's IPD.

1.3.2. Use alcohol wipe clean the setup. <???>

1.3.3. Ask the subject to the place the chin and the forehead at the chin rest. Sit firmly. Head be straight.

1.3.4. Adjust the height of chair, chin rest and the set-up inter-distance.

1.3.5. Ask subject to close left eye, open right eye.

1.3.6. Ask subject "Do you see clear and sharp text at the image?" if yes, go next. If no, go 1.3.4.

1.3.7. Ask subject to close right eye, open left eye.

1.3.8. Ask subject "Do you see clear and sharp text at the image?" if yes, go next. If no, the set-up inter-distance. go 1.3.7.

1.3.9. Ask subject "left and right image has significant height different?" if yes, go next. If no, go 1.3.4.

1.3.10. Ask subject leave the chair.<???>

1.3.11. Assembly the system and Trial test the motor operation of the set-up.<Why don't calibrate it first?>

1.3.12. Ask subject back to chin rest.

2. Practice

2.1.1. Explain double image and single image.

2.1.2. Open task1 at SGI.

2.1.3. Ask the subject to open both eyes.

2.1.4. Ask subject to see if he can see double image. If not, teach him.

2.1.5. Ask subject to see if he can see single image. If not, teach him.

2.1.6. Ask if the eyes can see one single image. If the answer is "No", investigate and ask the subject to relax the eye then try again. (Test subject's stereo ability)

2.1.7. Practice experiment procedure.

2.1.8. Most importantly, ask subject to give signal by knocking the desk by hand immediately when he gets single image.

3. Experiment Rundown

3.1. Procedure

3.1.1. Subject is require to close both eyes.

3.1.2. Perform the next task setting within 2 minutes.

3.1.3. After everything ok and 2 minutes, ask subject open both eyes. At the same time, start the timer.

3.1.4. When subject knocks on the desk, stop the timer.

3.1.5. Record.

3.1.6. Repeat 3.1.1 to 3.1.5. until all 18 runs finished.

3.2. During Task

3.2.1. The subject might need to read and speak out the text content.

3.2.2. Occasionally ask the subject question about the text in the task.

6.3.2 Consent Form

Consent Form

For Participating the Experiment of Micro-display

1. Name ____________________________
2. Do you have any form of illness? Yes/No
3. Do you have visual problem? Yes/No
4. Did you expose to stereoscopic 3D display in past one month? Yes/No
5. Have you suffered from any serious illness, e.g. diabetics (糖尿病) or epilepsy (癲癇症)? Yes/No
6. Are you under medical treatment or suffering disability which affects your daily life? Yes/No

If your answer is "Yes" to question (2), (3), (4), (5) or (6), please give details to the experimenter.

DECLARATION

I consent to take part in the experiment. My replies to the above questions are correct to the best of my belief, and I understand that they will be treated as confidential by the experimenter.

I understand that I may at any time withdraw from the experiment and that I am under no obligation to give reasons for withdraw declared above.

I undertake to obey the regulations of the laboratory and instructions of the experimenter regarding safety only to my right to withdraw declared above.

The purpose and methods of the experiment have been explained to me and I have had the opportunity to ask questions.

Signature of Subject ___________________ Date ____________________

Signature of Experimenter _________________ Date ____________________

6.3.3 Program source code in World Tool Kit

```
/*
 * task.cpp
 * Moving Letter
*/


#include <iostream.h>
#include <fstream.h>
#include <sys/time.h>
#ifndef WT_H
  #include "wt.h"
  #define WT_H
#endif
#ifndef WTCPP_H
  #include "wtcpp.h"
  #define WTCPP_H
#endif

#define Width   800     // Define room dimensions
#define Height  400
#define Length  2000

#define Parallax 6.0        // Eye parallax in cm
#define Pie     3.1415926   // Pie

static void  InitialScene ();
static void  SetTexture (WTgeometry *geom);

static void  DisplayMenu (void);// Show message
static void  InitialSensor (void);
static void  ActionFn (void);
static void  SensorUpdate2 (WTsensor *);

WTwindow    *window;    // Left  Eye
WTwindow    *window1;   // Right Eye
WTsensor    *sensor1;   // Glove
WTsensor    *sensor2;   // Headmount
WTviewpoint *view;

WTnode *root;
WTgeometry *room;
WTnode *room_node;
WTgeometry *text;
WTnode *text_node;
WTfont3d *font;

struct timeval  last_timerec;   // Count the time stamp
struct timezone last_timezrec;  // Fix the frame time
FLAG  ActivateSensor = FALSE;    // Sensor is activate or not
WTp3  OSensor1_p, OSensor2_p;
WTq   OSensor1_q, OSensor2_q;

int   Direction = 1;
int   Prec = 10;
float FrameRate = 30.0;          // Frame rate = 30 frames per second
float MoveSpeed = 500.0 / FrameRate;    // = 5m per second


void main(int argc, char *argv[])
```

```
{
    OSensor1_p[X] = 10000;
    OSensor2_p[X] = 10000;

       WTuniverse_new(WTDISPLAY_STEREO, WTWINDOW_DEFAULT);
       window = WTuniverse_getwindows(); // Left Eye Window Setting
       WTwindow_setposition(window, 8, 543, 629,
480);//SetPosition(window, int x0, int y0, int width, int height)
       WTwindow_setviewangle(window, 0.41887902);
    WTwindow_seteye(window, WTEYE_LEFT);

    window1 = WTwindow_next(window);    // Right Eye Window Setting
       WTwindow_setposition(window1, 645, 543, 629,
480);//SetPosition(window, int x0, int y0, int width, int height)
       WTwindow_setviewangle(window1, 0.41887902);
    WTwindow_seteye(window1, WTEYE_RIGHT);

    view = WTuniverse_getviewpoints();  // Viewpoint
    WTviewpoint_setparallax(view, Parallax);//SetParallax(viewpoint,
float x);
    WTwindow_setprojection(window,
WTPROJECTION_SYMMETRIC);//SetProjection(window, int type);
    WTwindow_setprojection(window1, WTPROJECTION_SYMMETRIC);

    DisplayMenu();  // Show message
    InitialScene();
    WTuniverse_setbgcolor(0x000);
       gettimeofday(&last_timerec, &last_timezrec);

    InitialSensor();
    WTuniverse_setactions(ActionFn);
    WTkeyboard_open();
       WTuniverse_ready();

       WTuniverse_go();             // Starts simulation

    WTsensor_delete(sensor1);
       WTsensor_delete(sensor2);
       WTuniverse_delete();         // All done
}


static void InitialScene()
{
    WTp3 abs_p;//3D with elements XYZ

    root  = WTuniverse_getrootnodes();

    room = WTgeometry_newblock( Width, Height, Length, TRUE );
    room_node = WTgeometrynode_new( root, room);
    SetTexture( room );

       abs_p[X] = 0;
    abs_p[Y] = 0;
       abs_p[Z] = Length/2;
    WTgeometry_translate( room, abs_p );//TranslateVerts(WtP3
offSet);

    font = WTfont3d_load("rcfont3d.nff");//WtFont3d(char *filename);
    text = WTgeometry_newtext3d( font, "VR" );//WtGeometry(WtFont3d
*font3d, char *string);
```

```
    WTgeometry_setrgb (text, 255, 50, 50);//Set text color

    text_node = WTgeometrynode_new( root, text); //Create a new node
       abs_p[X] = -3.73;
    abs_p[Y] =  4.64;
       abs_p[Z] = 1000;      // Orignally at 10m
    WTgeometry_translate( text, abs_p );

       //WTgeometry_getmidpoint:void
WTgeometry_getmidpoint(WTgeometry *geom,WTp3 p);
       //This function obtains the midpoint of a geometry’s extents box
in local coordinates.
       //The midpoint is returned in p.
    WTgeometry_getmidpoint( text, abs_p );
    WTmessage("Text Mid Point Position: %f, %f, %f \n", abs_p[X],
abs_p[Y], abs_p[Z]);
    // Originally 7.46, -4.64, 0.5
}

static void SetTexture (WTgeometry *geom)
{
    int i;
    WTpoly *poly;

    i = 1;
    for( poly=WTgeometry_getpolys(geom); poly; poly =
WTpoly_next( poly) )
    {
      if (i==4)
        WTpoly_delete( poly );

      else
      {
        WTpoly_setbothsides( poly, TRUE );
        WTpoly_settexture( poly, "wings", FALSE, FALSE);
         }

      i++;
    }
}

// Show message
static void DisplayMenu()
{
    WTmessage( "Controls:\n" );
    WTmessage( "'q' : Quit\n" );
    WTmessage( "'s' : activite/deactivite moving text\n" );
    WTmessage( "'?' : This help menu\n" );
    WTmessage("\n");
}


static void InitialSensor()
{
       WTserial *serial;
       unsigned char *buffer = new unsigned char[3];
/*
This function creates a serial port object. Once created, the serial
port object can be passed
in to the generic sensor construction function WTsensor_new (see page
13-7), when you
```

```
wish to create a sensor object whose records are obtained by
communication over the serial
port. However, if you are using the device-specific macro to create a
sensor object, it is
unnecessary to call WTserial_new because the macro creates the serial
port object by
calling WTserial_new.
*/
    serial=WTserial_new(SERIAL2, 38400);

       buffer[0] = 'B'; buffer[1] = '1'; buffer[2] = '\r';
//short WTserial_write(WTserial *serial,char *buffer,int length);
       WTserial_write(serial, buffer, 3);
//void WTmsleep(int msec);
       WTmsleep(1000);

       buffer[0] = 'B'; buffer[1] = '2'; buffer[2] = '\r';
       WTserial_write(serial, buffer, 3);
       WTmsleep(1000);

       buffer[0] = 'u'; // Set the Sensor to cm unit
       WTserial_write(serial, buffer, 1);
       WTmsleep(1000);

       WTserial_delete(serial);
       WTmsleep(1000);

       sensor1 = WTfastrak_new(SERIAL2, 1);
       sensor2 = WTfastrak_new(SERIAL2, 2);

       // Override the current sensor update function
       WTsensor_setupdatefn(sensor2, SensorUpdate2);//Head
}

// Head Mount
static void SensorUpdate2(WTsensor *sensor)
{
       WTq abs_q;
       WTp3 abs_p;
    WTq rotate;

       WTfastrak_update(sensor);
       WTsensor_getlastrecord(sensor, abs_p, abs_q);

       WTeuler_2q(0.0, Pie, 0.0, rotate);
       WTq_mult(abs_q, rotate, abs_q);

    if ((OSensor2_p[X] == 10000) && (ActivateSensor)) {
        WTq_copy(abs_q, OSensor2_q);
        WTp3_copy(abs_p, OSensor2_p);
    };

    if (ActivateSensor) {

        WTgeometry_getmidpoint( text, abs_p );

        // Go backward when reaching 10m
        if ( (1000 - abs_p[Z]) < Prec )
        {
          Direction = -1;
        }
```

```
        // Go forward when reaching 40cm
        if ( (abs_p[Z] - 40) < Prec )
        {
          Direction = 1;
        }

        // Simulate letter moving
           abs_p[X] = 0;
        abs_p[Y] = 0;
           abs_p[Z] = Direction * MoveSpeed;
           WTgeometry_translate( text, abs_p );

    };
}


static void ActionFn()
{
    long timediff = 0;
    struct timeval  timerec;   // Count the time stamp
    struct timezone timezrec;

    // Get the frame repeatedly until the 55ms frame time
       do {
      gettimeofday(&timerec, &timezrec);
      timediff = ((timerec.tv_sec-last_timerec.tv_sec)*1000)
        + ((timerec.tv_usec-last_timerec.tv_usec)/1000);
     } while (timediff < 1.0/FrameRate);

    last_timerec.tv_sec = timerec.tv_sec;
    last_timerec.tv_usec = timerec.tv_usec;

    short key = WtKeyboard::GetLastKey();
    switch (key) {
    case '?' :
      DisplayMenu();
      break;

    case 'q' :
      WTuniverse_stop();
      break;

    case 's' :
      if (ActivateSensor == TRUE) {
        ActivateSensor = FALSE;
      } else {
        ActivateSensor = TRUE;
      };
      break;

    };
}

)
```

6.4 Appendices for the main experiment

6.4.1 7-point tirdeness rating

0: no symptom

完全沒有同眼有關的症狀

1: Slight unpleasant symptom related to my eyes, however slight.

有微量同眼有關的症狀,無論幾微少

2: mild unpleasant symptom related to my eyes

有小量同眼有關的症狀

3: mild tiredness related to my eyes

有小量眼疲勞

4: mild to moderate tiredness related to my eyes

有小量至中量眼疲勞

5: moderate tiredness related to my eyes but can continue

有中量眼疲勞,但可以繼續

6: moderate tiredness related to my eyes, and want to stop

有中量眼疲勞,並且想停止

Note to Participant:

no = 無

slight = 微量

mild = 小量

moderate = 中量

6.4.2 Participates Screening procedure for main experiment

1. Volunteer arrives at the optometry clinic.
2. Experimenter welcomes the volunteer.
3. Experimenter briefly describes the aim, major content, cautions, timetable of the experiment to the subject. Also the remuneration details.
4. Experimenter describes the optometry screening test to the volunteer.
5. Experimenter asks the volunteer to fill in and sign a form about his/her consent to the screening test and the basic information and medical (incl. vision) information, and previous experience to stereoscopic micro-display.
6. Volunteer fills in and signs for the consent.
7. Experimenter and optometrist access the information to see if the volunteer is suitable for the experiment.
8. If yes, Experimenter informs the volunteer to attend the screening test now. If no, Experimenter informs the volunteer about the unsuitability and that volunteer can leave. Optometrist conducts the screening test.
9. After test, Experimenter and optometrist access the information to see if the volunteer is suitable for the experiment.
10. If yes, Experimenter accepts the volunteer to be the participant.
11. Experimenter informs the volunteer the result, and if the volunteer passes, Experimenter asks volunteer's consent to become participant. If the volunteer cannot pass, Experimenter informs the volunteer about the unsuitability and that volunteer can leave.
12. If Volunteer agrees to be Participant, Experimenter arranges the schedule to the participant.
13. Experiment reminds the pre-experiment cautions to the participant i.e. sleep well and take enough rest before experiment, stay one-self calm, avoid making the eyes tired. etc.
14. Subject to Optometrist's agreement, Experimenter gives the screening report (as a kind of remuneration) to all the screened volunteers. However, e.g. if a volunteer passed the screening test but deliberately refuses to become participant, Experimenter and Optometrist can opt to not give the screening report to that volunteer, or just give a simplified version.
15. Experiment finishes. Participant can leave the experiment venue.

6.4.3 Main experiment procedure

1 One day earlier, experimenter reminds volunteer to attend the experiment by phone.
2 Volunteer arrives at the optometry clinic.
3 Experimenter welcomes the volunteer.
4 Experimenter describes the aim, task content, procedures and regulations to the participant.
5 Experimenter asks the participant to fill in and sign a form about his/her consent to the experiment and the basic information and medical (incl. vision) information, and previous experience to stereoscopic micro-display.
6 Participant fills in and signs for the consent.
7 Experimenter describes participant the technical terms e.g. single image, double image etc.
8 Experimenter instructs participant what he / she has to do in the task.
9 Experimenter instructs participant the SSQ and 7-point rating.
10 Experimenter adjusts the IPD and shows the system to participant.
11 Experimenter instructs participant to try the system and experience the task.
12 If participant cannot see clearly or posture is not comfortable, experimenter adjusts the system.
13 When participant is ok, PRACTICE begins.
14 When participant completes the PRACTICE, participant starts to rest 10min in complete darkness to remove all effect from the previous works.
15 Experimenter asks participant the SSQ and 7-point rating, to see if participant rests enough.
16 If participant has some symptoms, let participant rest until no symptom. Allowable time is 10min. If over 20 min but symptom still exists, determine continue experiment or not subject to participant's condition.
17 If participant has no symptom, optometrist conducts pre-treatment measurement to participant, in the following sequence:
   17.1 VA at far and near
   17.2 Laterial phoria at far and near
   17.3 Vertical phoria at far and far
   17.4 Fixation disparity
   17.5 Stereopsis

17.6 Dark Focus (by autorefractor; baseline at bright environment and then continuously measurement at complete darkness for 5 min. This 5 min also serve as rest period to the participant.)

18 Experimenter asks participant the SSQ and 7-point rating, as the pre-treatment rating.

19 EXPERIMENT (i.e. treatment) begins to participant.

20 Experimenter asks participant the 7-point rating every 2 minutes.

21 After 30 minutes, experimenter asks participant the SSQ and 7-point rating, as the post-treatment rating. In this period (about 1 min), participant still views the micro-display.

22 Optometrist conducts post-treatment measurement to participant, in the following sequence:

22.1 Dark Focus (by autorefractor; baseline at bright environment and then continuously measurement at complete darkness for 5 min)

22.2 Laterial phoria at far and near

22.3 Vertical phoria at far and far

22.4 Fixation disparity

22.5 Stereopsis

22.6 VA at far and near

23 Experimenter interviews (de-briefs) the participant about the comment to the experiment and the feeling about sickness / tiredness.

24 Experimenter gives the remuneration to participant and participant acknowledges the receipt.

25 Experimenter schedules the next experiment date and time with the participant.

26 Experiment finishes. Participant can leave the experiment venue.