Eye fatigue when viewing stereo images presented on a binocular display: effects of matching lens focus with stereoscopic depth cues

by

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by

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This is to certify that I have examined the above MPhil thesis

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the thesis examination committee have been made.

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31st October 2008

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The effects of matching lens focus with dynamically changing stereoscopic depth cues on the eye fatigue level when viewing a binocular micro-display

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Abstract

When viewing a real object, our eyes will accommodate to focus at the object. At the same time, our eyes will also verge so that the visual axis of both eyes will point towards that object. In other words, the vergence of eyes will change in accordance to the accommodation of the eyes. However this relationship may be disturbed when viewing stereo images with changing stereo depths presented on a binocular display with fixed lens focus. The incompatibility between the varying stereo depth and the fixed lens focus can post an unnatural demand on human vergence eye movements. This may cause eye fatigue. An experiment has been conducted to investigate the levels of eye fatigue caused by viewing stereo images with changing stereo depths on a binocular display with compatible and incompatible lens focuses. Four viewing conditions have been studied and they exhaust the factorial combinations of two lens focus (40cm and 200cm) and two changing stereo depth cues (40cm ± 0.3 dioptres and 200cm ± 0.3 dioptres). This design examines the effects of lens focus, stero depth, and their interactions (i.e., compatibility between lens focus and stereo depth). In this study, we are interested in the compatibility effects when the lens focus or stereo depth is controlled at 40cm and 200cm, respectively.

When using a binocular display with fixed lens focus of 200cm, viewing stereo images with

incompatible stereo depths (40cm) can significantly increase the rated levels of eye fatigue (p<0.001, $F_{1,383}$ = 33, ANOVA). This is an important finding and carries serious implications to those manufacturers of binocular displays with fixed lens focus of 200cm (e.g., iMD Ltd.). Unfortunately, adjusting the lens focus of the displays to 40cm to match the stereo depths of the images did not result in significant reduction in eye fatigue (p>0.5, $F_{1,383}$ = 0.36, ANOVA). The lack of benefits is due to an opposite confounding effects of accommodation on eye fatigue: as the lens focus is reduced to match with the stereo depth, the accommodative demand on the eyes is increased. The former reduces the levels of eye fatigue while the latter does the opposite. Data also indicate that when the confounding effect of accommodation is in agreement with the compatibility effects between lens focus and stereo depth, very significant reduction in rated levels of eye fatigue are reported when lens focus is changed from 40cm to 200cm in order to match with images of stereo depths of 200cm ((p<0.001, $F_{1,383}$ = 55.5, ANOVA). Further discussion and implications to the design of binocular displays can be found in the thesis.

CHAPTER 1

INTRODUCTION

1.1 Background

1.1.1 An introduction to accommodation and vergence when viewing real world objects

When viewing a real object in the real world, our eyes will accommodate to focus at the object. At the same time, our eyes will also verge or turn inwards so that the visual axis of both eyes will point towards the object. (Figure 1.1a & 1.1b) In other words, the vergence of eyes will change in accordance to the accommodation of eyes.

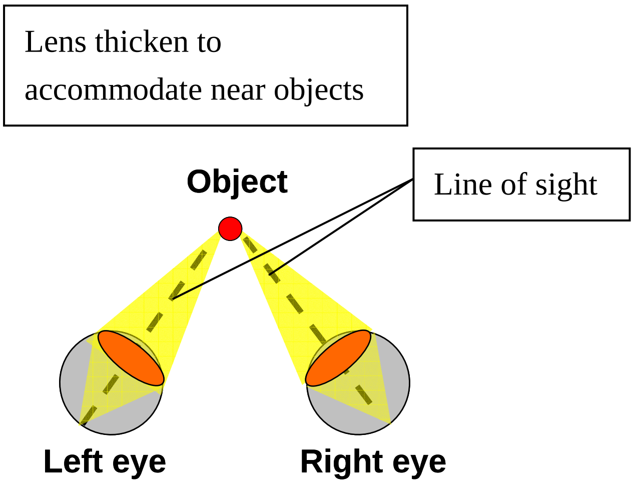

Figure 1.1a Eyes looking a near object

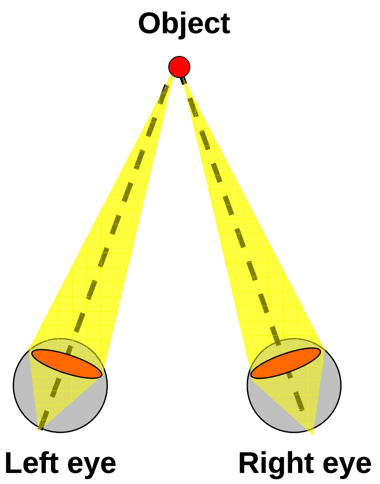

Figure 1.1b Eyes looking a far object

1.1.2 An introduction to binocular stereoscopic display

A binocular head-mounted display (HMD) usually consists of two small screens (micro-displays) with lens in front of the screens to present magnified images to each eye, respectively. The object as viewed from the left perspective is presented as an image on the left screen, while the right perspective view of the object is presented as an image on the right screen. When both eyes see their corresponding images, the eyes will converge to fuse the two images into a single stereoscopic image with appropriate perceivable depth. (Figure 1.2) An example of a typical HMD is shown in Figure 1.3.

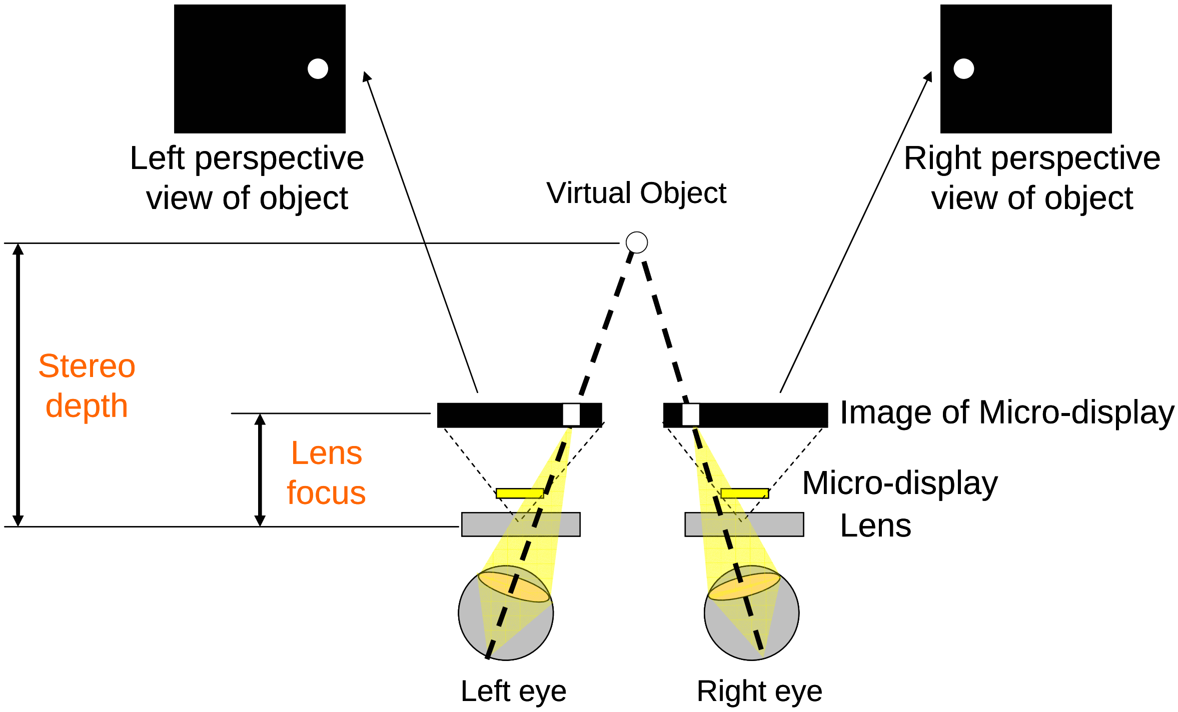

Figure 1.2 Viewing with HMD micro-display

Figure 1.3 Photo of a typical HMD (Adopted from Fifth Dimension Technologies, http://www.5dt.com/products/ihmd03.html)

1.2 Relationships of accommodation and vergence responses when viewing a binocular stereoscopic display

When the images on the micro-display are presented to both eyes so that the virtual object is located far behind the images projected from the micro-display, we have a mismatched condition of stereo depth larger than lens focus (Figure 1.4). In this condition, the eyes will accommodate to the lens focus for clear images and the vergence response will enable the eyes to fixate to the virtual object which is converged to a virtual depth behind the focal distance of the images projected from the micro-display.

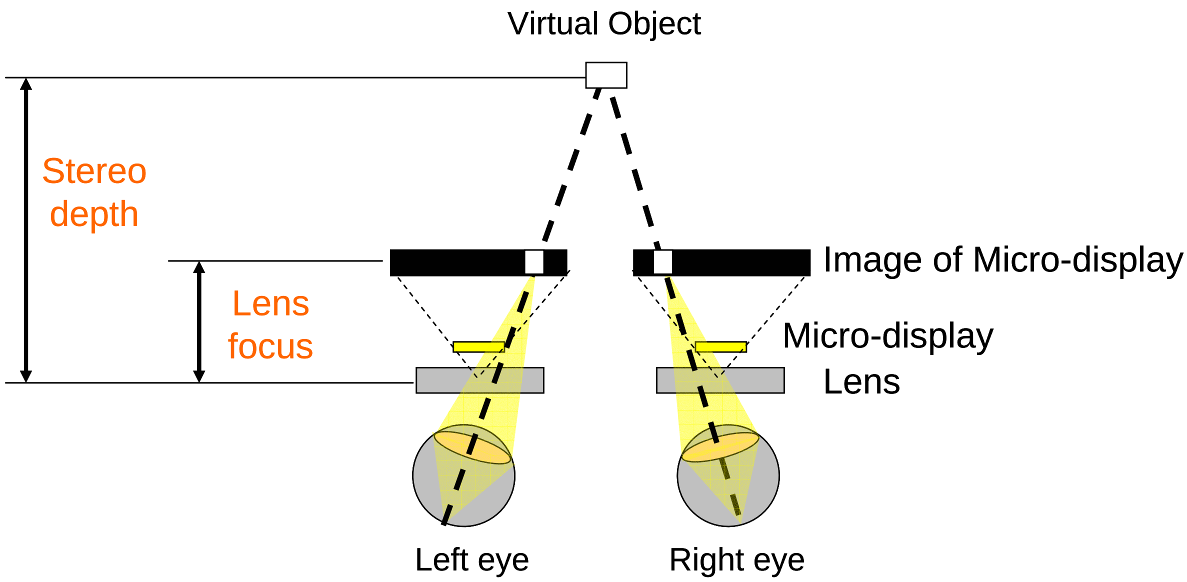

Figure 1.4 A mismatched condition of stereo depth larger than lens focus when viewing a binocular stereoscopic display (NB: the virtual depth is longer than the focal distance of the images projected from the micro-display).

On the other hand, when the images on the micro-display are presented to both eyes so that the virtual object is located far in front of the images projected from the micro-display, we have a mismatched condition of stereo depth smaller than lens focus. (Figure 1.5) In this condition, the eyes will accommodate to the lens focus for clear images and the vergence response will enable the eyes to fixate to the virtual object which is converged at a virtual depth that is in front of the focal distance of the images projected from the micro-display.

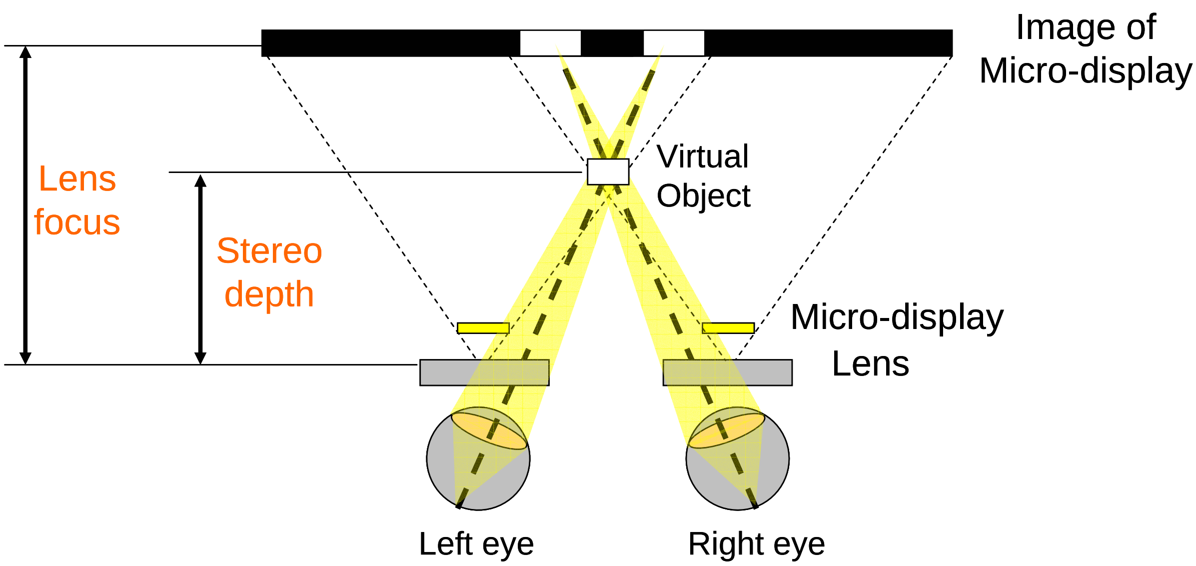

Figure 1.5 A mismatched condition of stereo depth smaller than lens focus when viewing a binocular stereoscopic display (NB: the virtual depth is shorter than the focal distance of the images projected from the micro-display).

When the images on the micro-display are presented to both eyes so that the virtual object is located at the image of micro-displays, we have a matched condition of stereo depth equal to lens focus (Figure 1.6). In this condition, the focal length of the images presented from the micro-display and the verged virtual depth of the images are the same.

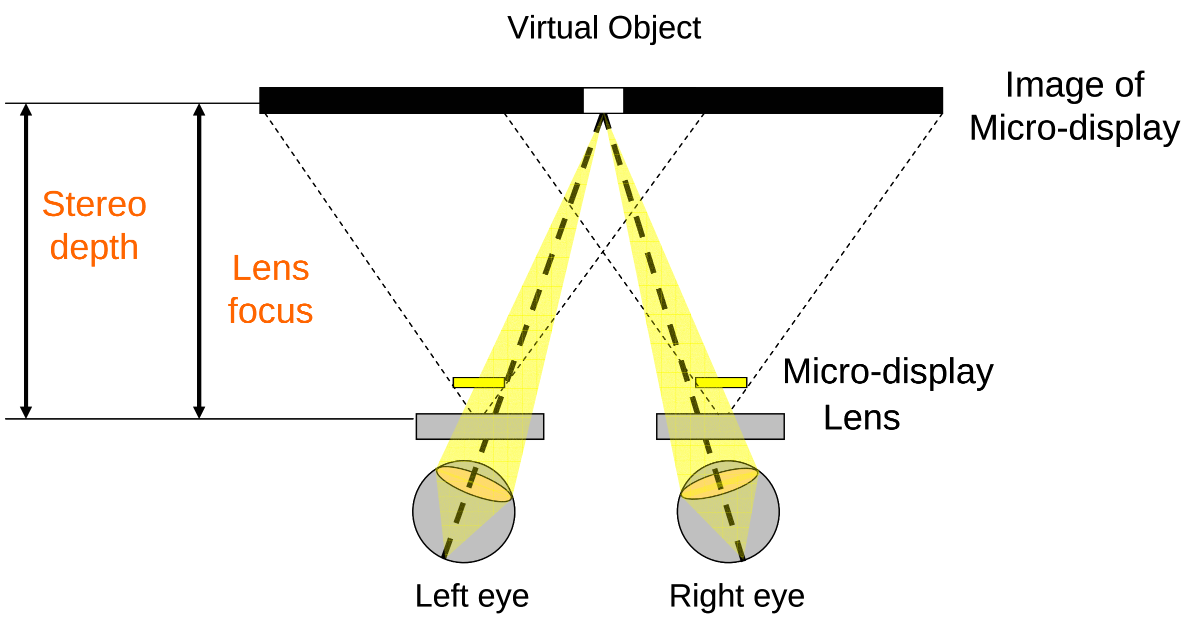

Figure 1.6 A matched condition of stereo depth equal to lens focus when viewing a binocular stereoscopic display.

1.3 Mismatch between accommodation and convergence when viewing a binocular stereoscopic display with fixed lens focus

When viewing a moving virtual object with varying stereo depth using a binocular display. Since the lens focus is fixed, the eyes will accommodate to the fixed lens focus of the display to obtain clear images but vergence response has to dynamically be changing according to the changing stereo depth cues. This creates a mismatch between accommodation and vergence responses.

1.4 Literature Review

1.4.1 Studies concerning eye fatigue have been many but studies focus on matching lens focus and stereoscopic depth in stereoscopic displays are few

It is well know from literature that prolonged viewing of visual display terminal or mono display can cause eye fatigue or visual stress. (Rash. 2008, Wu et al. 2007, Goo et al. 2004, Balci. & Aghazadeh. 2003, Mocci. 2001, Nakaishi. & Yamada. 1999, Ziefle. 1998, Chi. & Lin.

1998, Jaschinski. 1998, Lie. & Watten. 1994, Watten. et al. 1992, Miyao et al. 1989, Kruza. 1988, Iwasaki. & Kurimoto. 1987, Wilkinson. & Robinshaw. 1987, Dainoff. 1981) Such kinds of display terminals are usually monocular, that is, they consist of only one single display presented to the eyes of viewer. Also, viewers will not have a stereoscopic depth cue when viewing three dimensional images in such kinds of display.

1.4.2 Review of studies examining effect of matching lens focus with stereoscopic depth in stereoscopic displays

1.4.2.1 Studies reporting eye fatigue measurements

Only five studies have studied the levels of eye fatigue caused by viewing stereoscopic images presented in micro-displays. They are reviewed as follows.

Yano *et al*. (2004) reported a significant increase in the level of eye fatigue when viewing stereoscopic HDTV images with stereo depths longer than the focus distance and were outside the depth of focus

Miyao *et al.* (1996) reported that prolonged viewing of stereoscopic images with varying stereo depth between 0.8m and 2m presented on a CRT display located at 1m from subjects wearing liquid crystal shutter glasses caused loss of accommodation and task performance. In their study, most subjects complained of stiffness in neck and shoulders, eye pain, and dry eyes after the experiment. However, only the mismatched condition was studied in their experiment and there was no matched condition for comparison.

Emoto *et al*. (2005) reported the closest study to the work of this thesis. Subjects were required to view stereoscopic images with changing stereo depth cues displayed on HDTV. A pair of variable prisms was installed in front of eyes, the prism power was varied to produce varying vergence load on eyes. In a mismatched condition, no lens was used. In a matched condition, compensation lenses were used to match vergence with accommodation. It was found that in mismatched condition, the chance of seeing double image was higher than matched condition. There is no significant difference on the subjective visual fatigue ratings. Although, both match and mismatch conditions were explored but the viewing distance is fixed at 30cm. In other words, matching effects between vergence and accommodation at far viewing distance (say 200cm) was not investigated.

Kuze and Ukai (2008) reported that viewing stereoscopic moving images projected on a 90 inches back-projected screen using anaglyph method at a fixed distance of 2m produced significantly higher eye strain ($p < 0.001$), focus difficulty ($p < 0.05$) and general discomfort ($p < 0.05$) when compared with viewing non-stereoscopic moving images projected on the same screen. However, matched condition when viewing stereoscopic moving images was not explored at all.

Mon-Williams and Wann (1998) studied the deficits in binocular vision and eye fatigue symptoms on a 10-point scale after 10 minutes exposure to a cross sign oscillate between 40cm to infinity (frequency 0.3 Hz). They reported significant changes in visual acuity, symptoms, distance heterophoria, distance-associated and near-associated heterophoria. However, the distance between the subject and the display was fixed at 40cm and all virtual objects had stereo depth behind the display. That is, only the condition with one focal length with mismatched focus distance shorter than the stereo depth was studied.

1.4.2.2 Studies reporting binocular status without eye fatigue measurements

In addition to the five studies reviewed in the last section, studies reporting binocular status when viewing stereoscopic images have been found (Sugihara *et al.*, 1999; Okada *et al.*

2006; and Takeda *et al.* 1999). However, none of these studies reported eye fatigue data. Sugihara *et al.* (1999) developed a stereoscopic display with dynamic changing lens focus. Their display system had two separate display screens for each eye, with movable optics in front of the screens to provide a compensation function. They exposed viewers to a mis-matched condition with changing stereo image depth and lens focus was fixed at 200cm and a matched condition with changing stereo image depth and changing lens focus to provide correspondence between vergence and accommodation. It was found that the contraction time of accommodation decrease significantly in the matched condition over the experiment period. Also, the variability in contraction time under the mismatch condition was larger than that in the matched condition. They mentioned that fatigue data was measured, but was not reported.

Okada *et al.* (2006) studies the effects of 3 levels of target blur on accommodation and vergence response under matched and mismatched conditions between accommodation and vergence. Subjects were viewing stereoscopic LCD laptop PC with parallax barrier. In their study, the viewing distance was set at 50 cm and the stereo depth changed from 50 cm (matched condition) to 33 cm (mismatched condition) and 25 cm (mismatched condition). The accommodative demands during mismatched conditions were found to be significantly higher than that found in matched condition. Also, accommodative demand increases with target blur under mismatched conditions. While under matched condition, accommodative demand does not increase with target blur. Eye fatigue was not measured in their study.

Takeda *et al.* (1999) studied the decoupling of accommodation and vergence when viewing a stereoscopic display with varying virtual stereoscopic depth cues. Fluctuations in accommodation were observed when subjects were viewing stereoscopic display. However, no fatigue measurement data was collected.

1.5 Research Gap

Although eye fatigue has been the subject of many studies, the focuses of most studies have not been on comparing the effects of match and mismatch between vergence with accommodation responses (Kuze and Ukai. 2008). For those studies examining the effects of matching vergence with accommodation responses on eye fatigue, only a single lens focus has been studied (Emoto *et al*. 2005, Yano *et al.* 2004). In some studies, only the mismatched condition was examined and matched condition of viewing stereo images was not studied (Mon-Williams and Wann. 1998, Miyao *et al.* 1996).

This leaves a research gap in studying the levels of eye fatigue when viewing stereoscopic images presented on a HMD with matched and mismatched lens focus at both near and far accommodation.

CHAPTER 2

EXPERIMENT

2.1 Objectives and hypothesis

The objectives of the experiment is to study the levels of eye fatigue when viewing stereoscopic micro-display images with dynamically changing stereoscopic depth cues under matched or unmatched lens focus.

It was hypothesized that the subjects would have significantly lower eye fatigue when the lens focus was equal to (i.e. matched with) the stereo depth. When the lens focus matched with the stereo depth, the participants did not experience conflict between accommodation and vergence. Consequently, the participants could have lower level of eye fatigue.

Because there were four factorial combinations of the lens focus and stereo depth, four hypotheses (H1 – H4) were formed:

H1: at lens focus 40cm, the eye fatigue level at stereo depth 40cm ± 0.3D (a matched condition C1) will be significantly lower than that of at stereo depth 200cm ± 0.3D (a mismatched condition C3).

H2: at lens focus 200cm, the eye fatigue level at stereo depth 200cm ± 0.3D (a matched condition C2) will be significantly lower than that of at stereo depth 40cm ± 0.3D (a mismatched condition C4).

H3: at stereo depth 40cm ± 0.3D, the eye fatigue level at lens focus 40cm (a matched condition C1) will be significantly lower than that of at lens focus 200cm (a mismatched condition C4).

H4: at stereo depth 200cm ± 0.3D, the eye fatigue level at lens focus 200cm (a matched condition C2) will be significantly lower than that of at lens focus 40cm (a mismatched condition C3).

2.2 Methods

2.2.1 Apparatus

2.2.1.1 The experimental binocular micro-display system

2.2.1.1.1 The micro-displays

Two liquid-crystal-on-silicon (LCoS) micro-displays were used as the display panel for left eye and right eye respectively. The micro-display units are supplied by Integrated Microdisplays Limited (iMD), Hong Kong, PRC. The model is iSDTV704C. The display resolution is 688 (Horizontal) x 480 (Vertical). The display panels work with a hardware driver with proprietary driving scheme. The hardware driver accepts two VGA input streams and converts the data for the corresponding panel. The size of the display is 12mm (width) by 9mm (height). The display area is 0.56" diagonally. The colour of the display is RGB 24-bit. The diagonal field of view is 30 degree for each eye. The luminance is 0.44 lux for the left display and 0.47 lux for the right display. A chroma meter (Minolta Camera Co. Ltd. Model: CS-100, See figure 2.0 for photo of the instrument) was used to measure the luminance. The measurement were taken 30 times and averaged to obtain the luminance value.

Figure 2.0 Chroma meter used for measuring the luminance of the microdisplay.

2.2.1.1.2 The lens

A pair of lens was installed in front of the pair of micro-displays. The lens was mounted in a threaded lens fixture so that user can adjust the distance between the displays and the lens by turning the threaded lens fixture to achieve adjustable lens focus from 40cm to 200cm.

Lens focus is the virtual image distance. It is determined by the object distance (i.e. the distance between the micro-display screen and the lens) and the focal length of the lens (i.e. the lens focusing power).

According to the lens formula, the relationship of lens focus, object distance and focal length of the lens is:

$1/u = 1/v + 1/f$

Where:

v = lens focus (i.e. virtual image distance)

u = object distance (i.e. the distance between the micro-display screen and the lens)

f = focal length of the lens

Rearrange the formula, we get:

$v = (u*f) / (f-u)$

Therefore, by changing the distance between the lens and the micro-display (u), the lens focus (v) can be changed to achieve the distance of either 40 cm or 200 cm.

Figure 2.1 and 2.2 illustrate how the change of object distance varies the lens focus. When comparing figure 2.1 with 2.2, it can be seen that the lens moves towards the micro-display (O). Since, the distance from the lens to the micro-display (object distance) is reduced from L1 to L2. Therefore, the lens focus (image distance) decreases from d1 to d2. The closer the lens to the micro-display, the smaller the lens focus. In the display system, to bring the lens focus from infinity to 40cm, the lens movement distance is around 2mm.

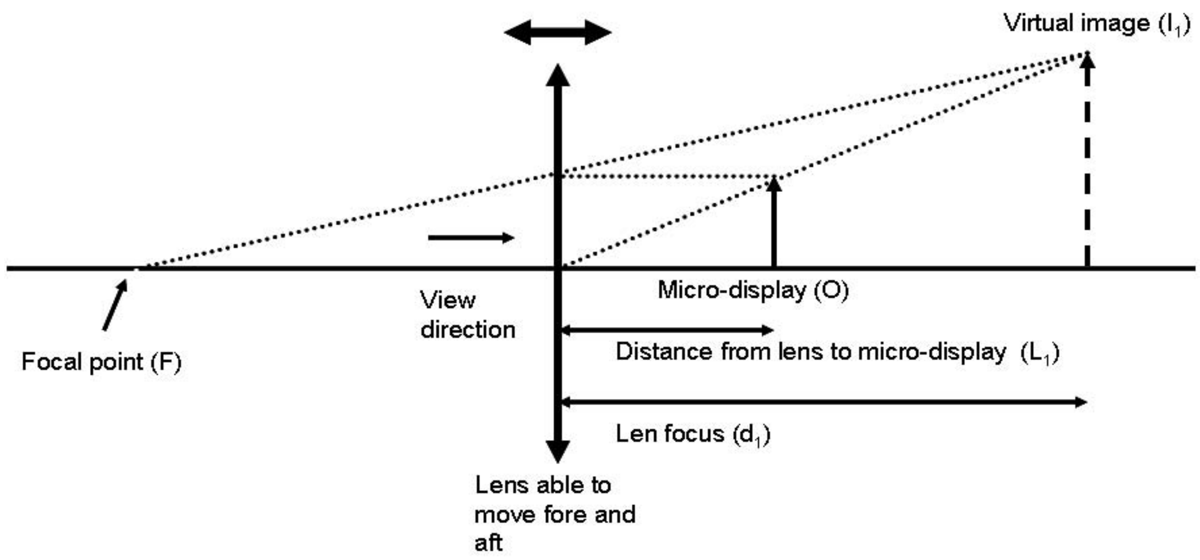

Figure 2.1 A schematic diagram showing the formation of a virtual image at the micro-display system. Not all units of the micro-display system are drawn, e.g. polarized beam splitter. (Adopted from Wong W.S. 2007)

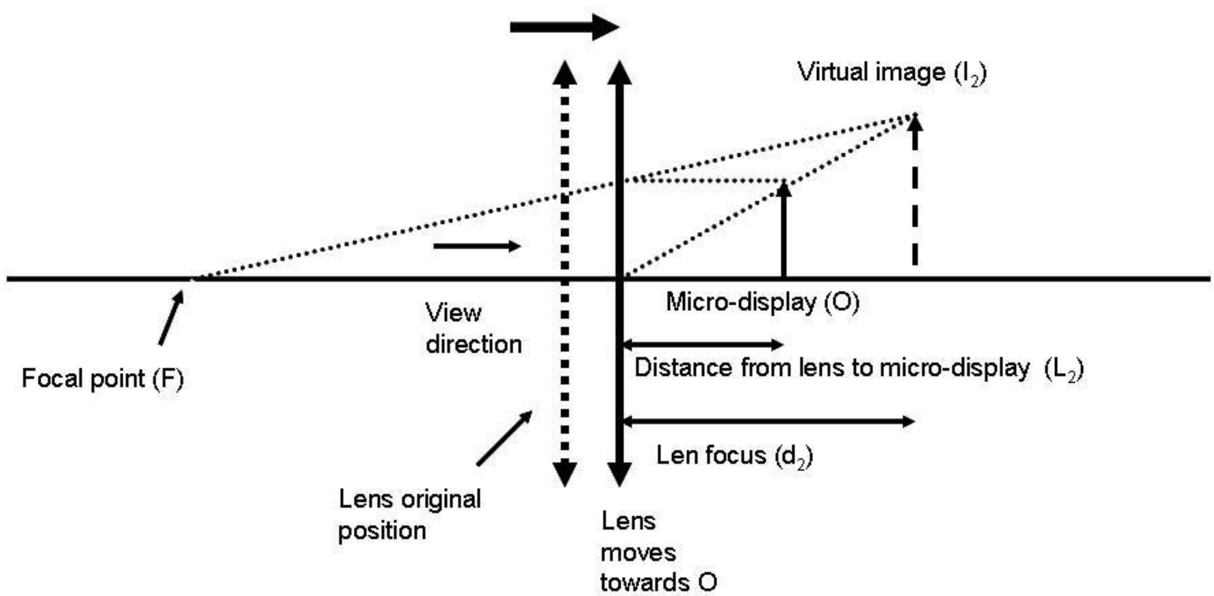

Figure 2.2 A schematic diagram showing how the change of the distance between the micro-display screen and the lens can change the lens focus. (Adopted from Wong W.S. 2007)

2.2.1.1.3 Lens and micro-display assembly

A sectional drawing of the display system used in the experiment is shown in Figure 2.3. It mainly consists of four parts. The micro-display LCD panel is mounted at the back of a black PBS housing. Inside the PBS housing is a polarized beam splitter (PBS) that directs the light from an LED on top of PBS housing to the LCD panels. In front of the black housing is a lens that will magnify the image displayed on the micro-display LCD panel and projects the image at a specified lens focus distance. The lens is held by the lens fixture. When the lens fixture screws in and out dynamically, the distance between the lens and the micro-display screen changes, and so the lens focus could be adjusted dynamically.

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.

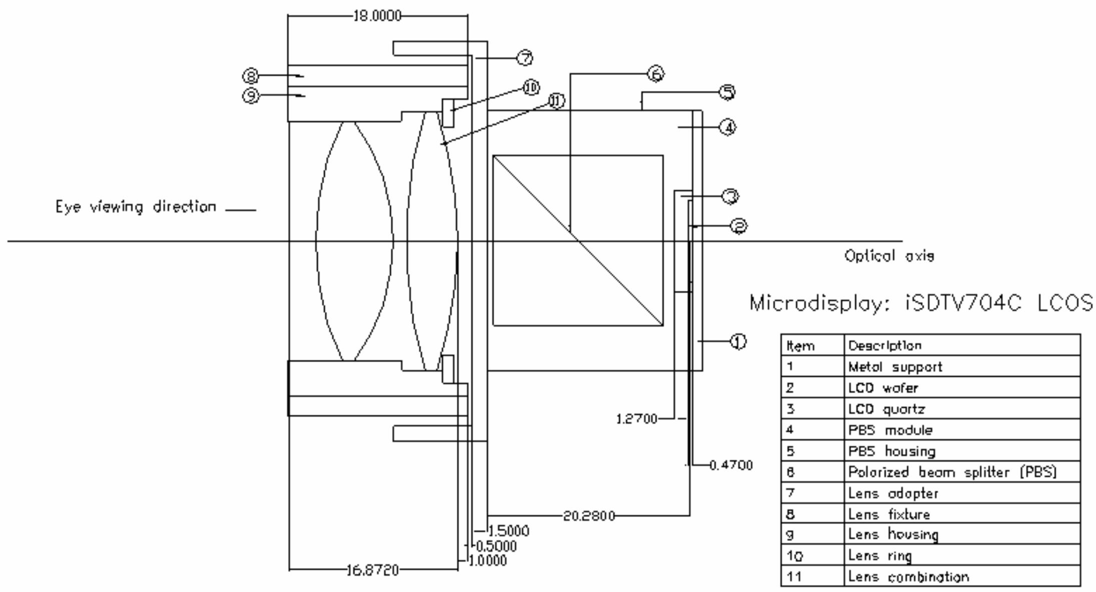

Figure 2.3 A sectional drawing showing the internal structure of the micro-display system. The custom-built lens adapter assembled onto the retrofit iSDTV704C micro-display system. Not all components are drawn e.g. the threads on the lens fixture and lens adapter. (Adopted from Wong W.S. 2007)

2.2.1.1.4 Platform and Chin Rest

The whole lens and micro-display assemblies (for left eye and right eye) were installed on a metallic platform. The platform was used to hold the display system at eye level of subject. Figure 2.4 shows a photo of the front view of the experimental set-up.

The distance between the optical centers of the pair of lens can be adjusted to match with inter-pupillary distance (IPD) of different subjects. The adjustable range is 53 mm – 70 mm.

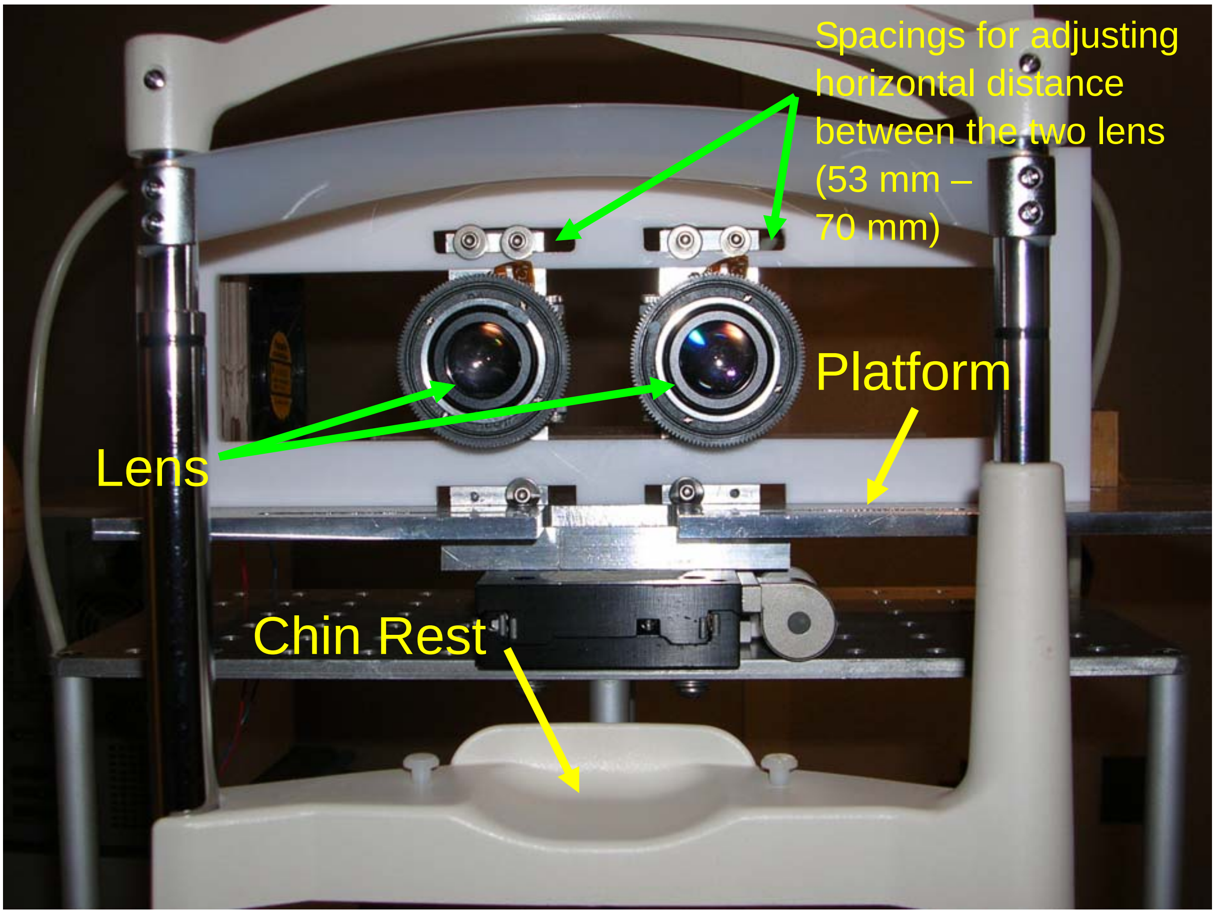

Figure 2.4 A photo showing the front view of the experimental set-up.

Chin Rest was used to fix the subject's head and eyes position. (Figure 2.5) The height of the chin rest is adjustable to accommodate different sitting eye-height of subjects. Figure 2.6 shows a subject viewing the display system through the pair of lens.

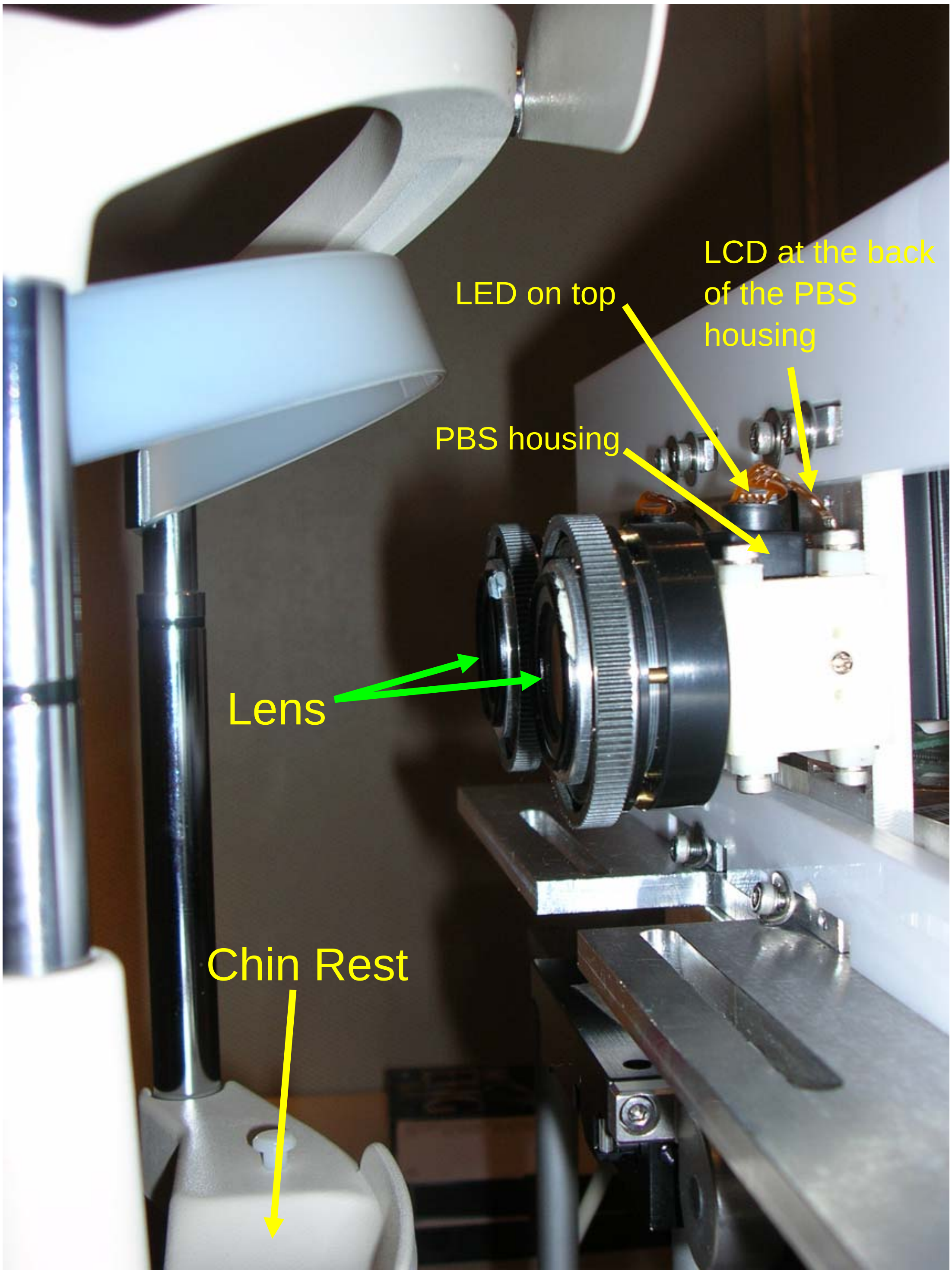

Figure 2.5 A photo showing the side view of the experimental set-up.

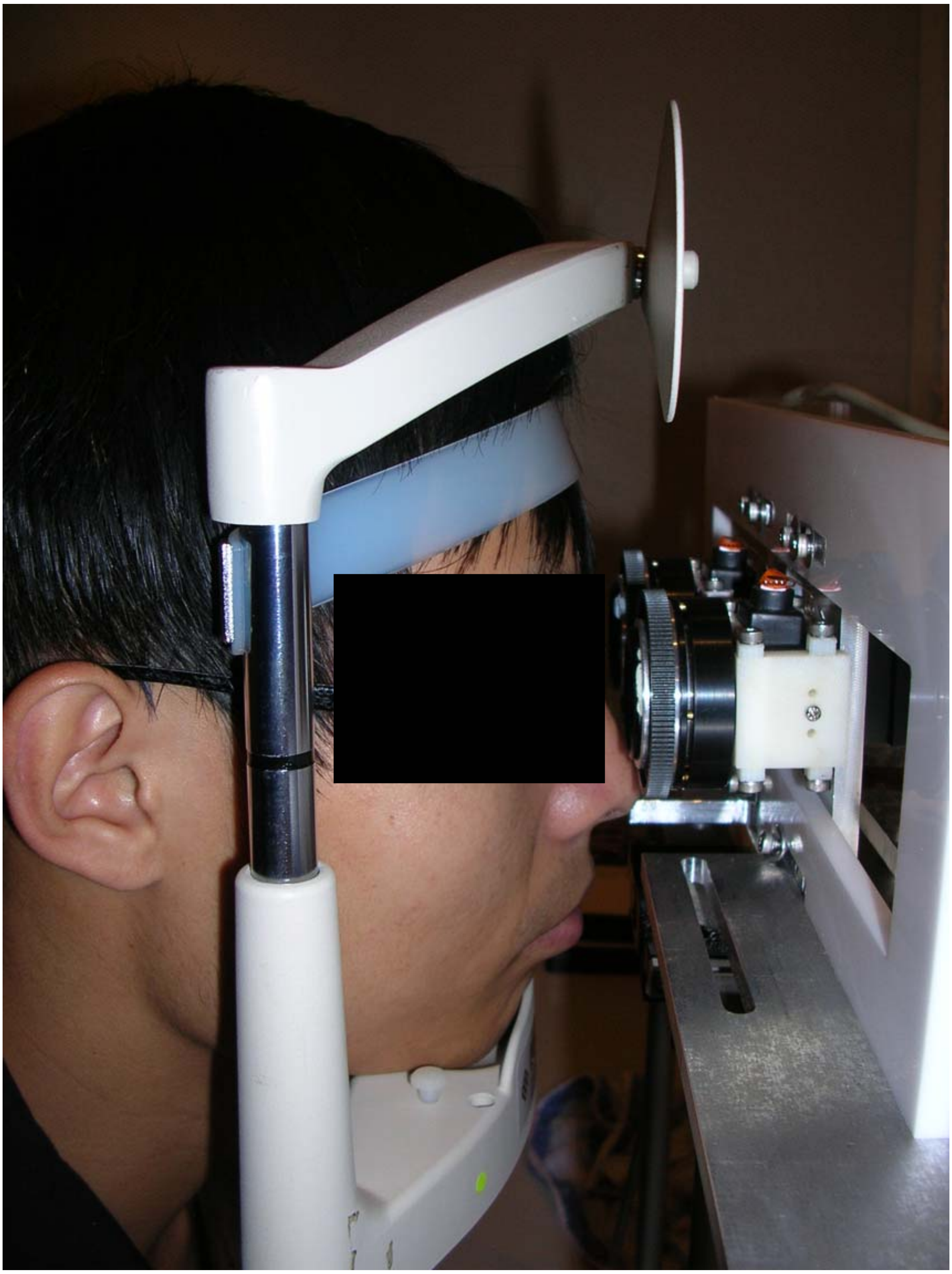

Figure 2.6 A photo showing a subject viewing stereoscopic images displayed on the micro-display through the lens.

2.2.1.1.5 Display driver

The image content displayed on the LCD was driven by a display card (Inno3D nVidia GeForce 6200) inside a Pentium4 computer. The graphics display card has two outputs. (Figure 2.7) Each output drives one LCD display. (Figure 2.8) The computer was set to display in horizontal span mode. (i.e. 1280 x 480 pixels)

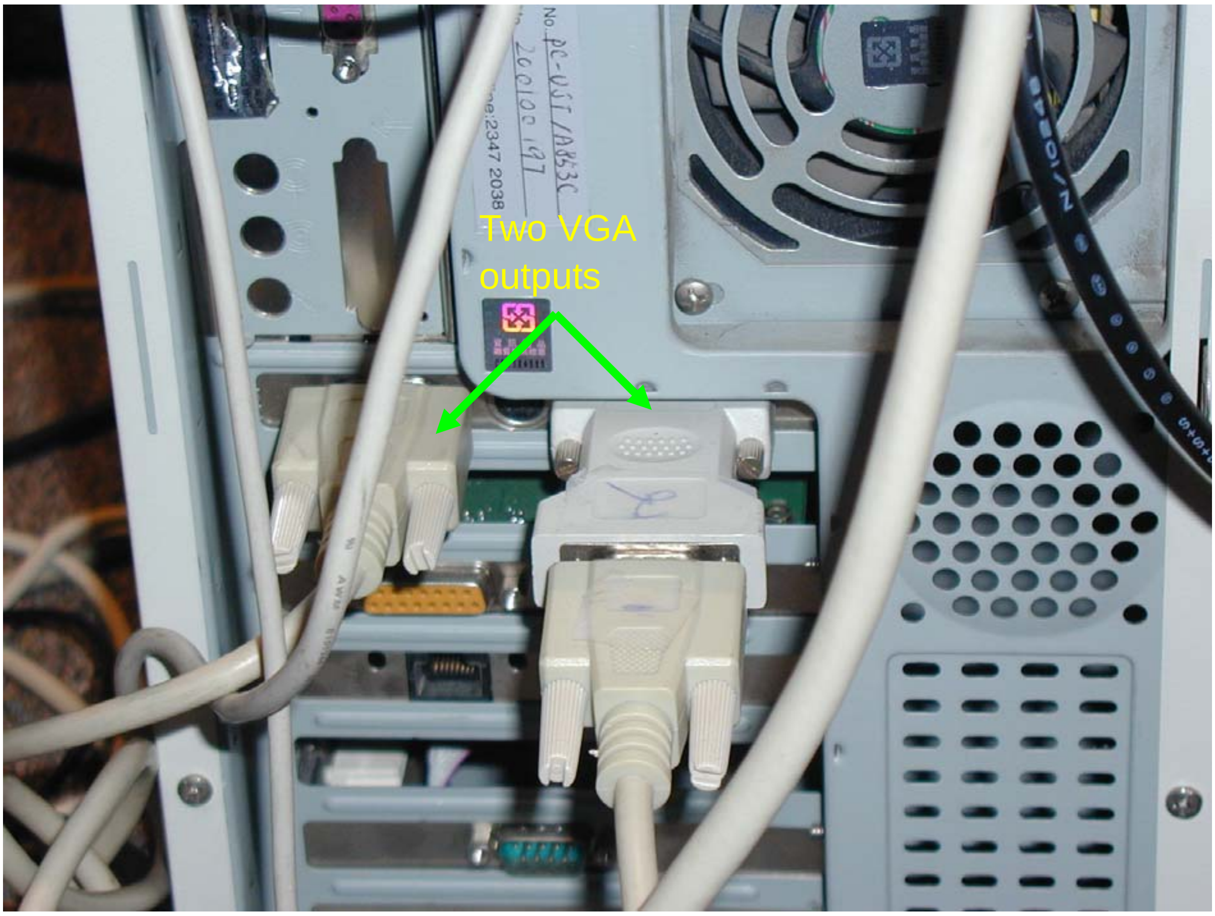

Figure 2.7 A photo showing the two VGA display output from the back of the computer to drive the two LCDs.

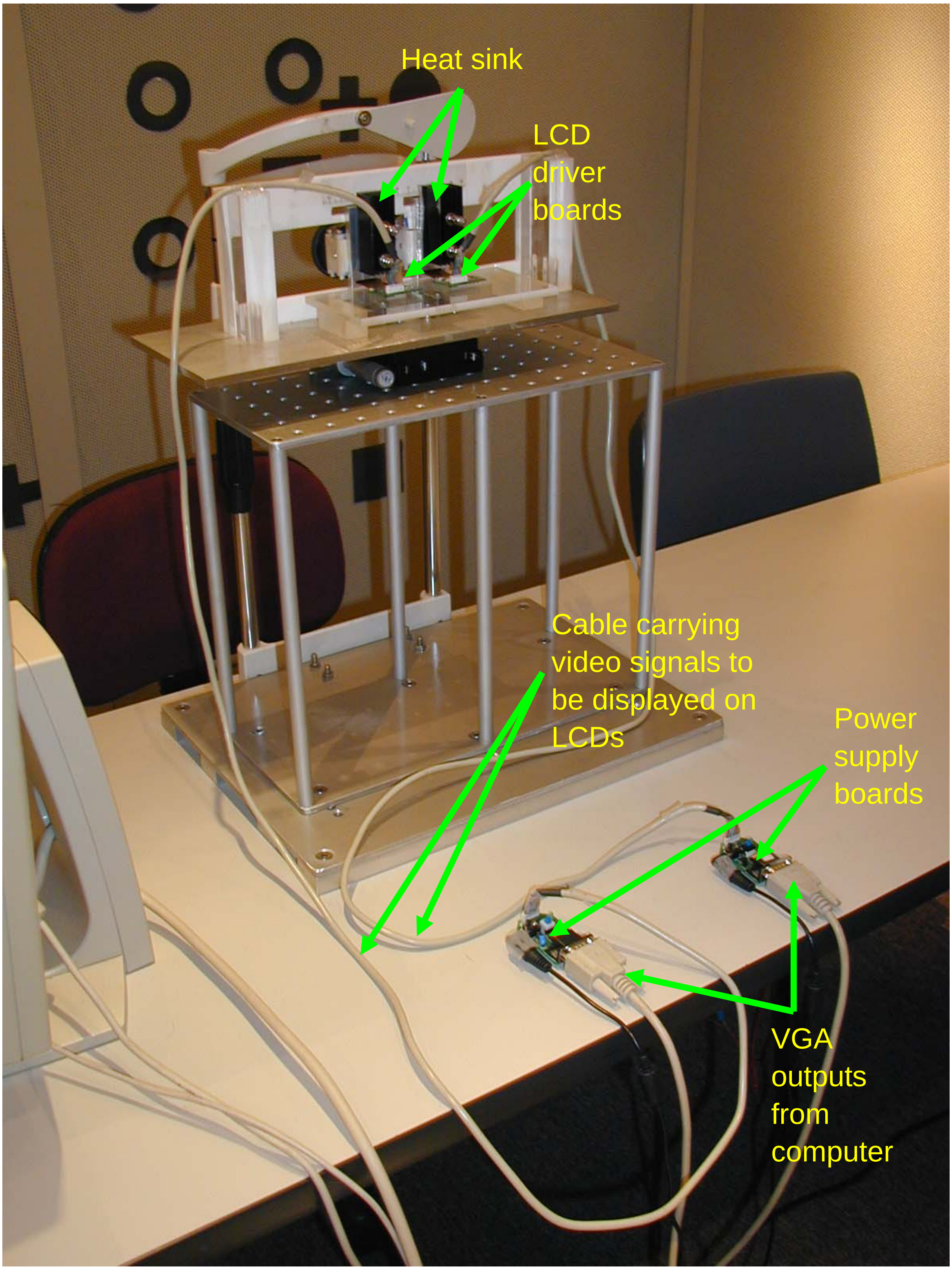

Figure 2.8 A photo showing the back view of the experimental setup. The VGA outputs from the computer are used to diver the two LCDs. Heat sinks are installed at the back of the LCDs to dissipate heat.

2.2.1.1.6 The whole layout

Figure 2.9 shows the layout of the experimental set-up. A computer screen was used by the experimenter to monitor the stimuli which is the same one displayed on the LCD. The experimenter can also monitor the status of the subject easily and check whether the response from the subject is consistent with what is displayed on the LCDs with the help of the computer screen.

2.2.1.2 The Acoustic Room

The experiment was conducted in the acoustic room supplied by Industrial Acoustics Company (H.K.) Ltd (model no: IAC 400A-CT). This room has sound isolation walls which provide an experimental environment with controlled noise level.

2.2.1.3 Vision tester

A vision tester (Stereo Optical Co. Inc, Model 2000, made in USA) was used to perform a set of visual test on subjects so that suitable subject can be selected to do the experiment. The set of test performed on the subjects include:

1. Visual Acuity of both eyes looking at a target distance of 20 feet (far point VA)
2. Visual Acuity of right eyes looking at a target distance of 20 feet (far point VA-R)
3. Visual Acuity of left eyes looking at a target distance of 20 feet (far point VA-L)
4. Visual Acuity of both eyes looking at a target distance of 14 inches (near point VA)
5. Visual Acuity of right eyes looking at a target distance of 14 inches (near point VA-R)
6. Visual Acuity of left eyes looking at a target distance of 14 inches (near point VA-L)
7. Stereo Depth perception at 20 feet (stereoacuity).
8. Color Discrimination Test to identify any color blindness.

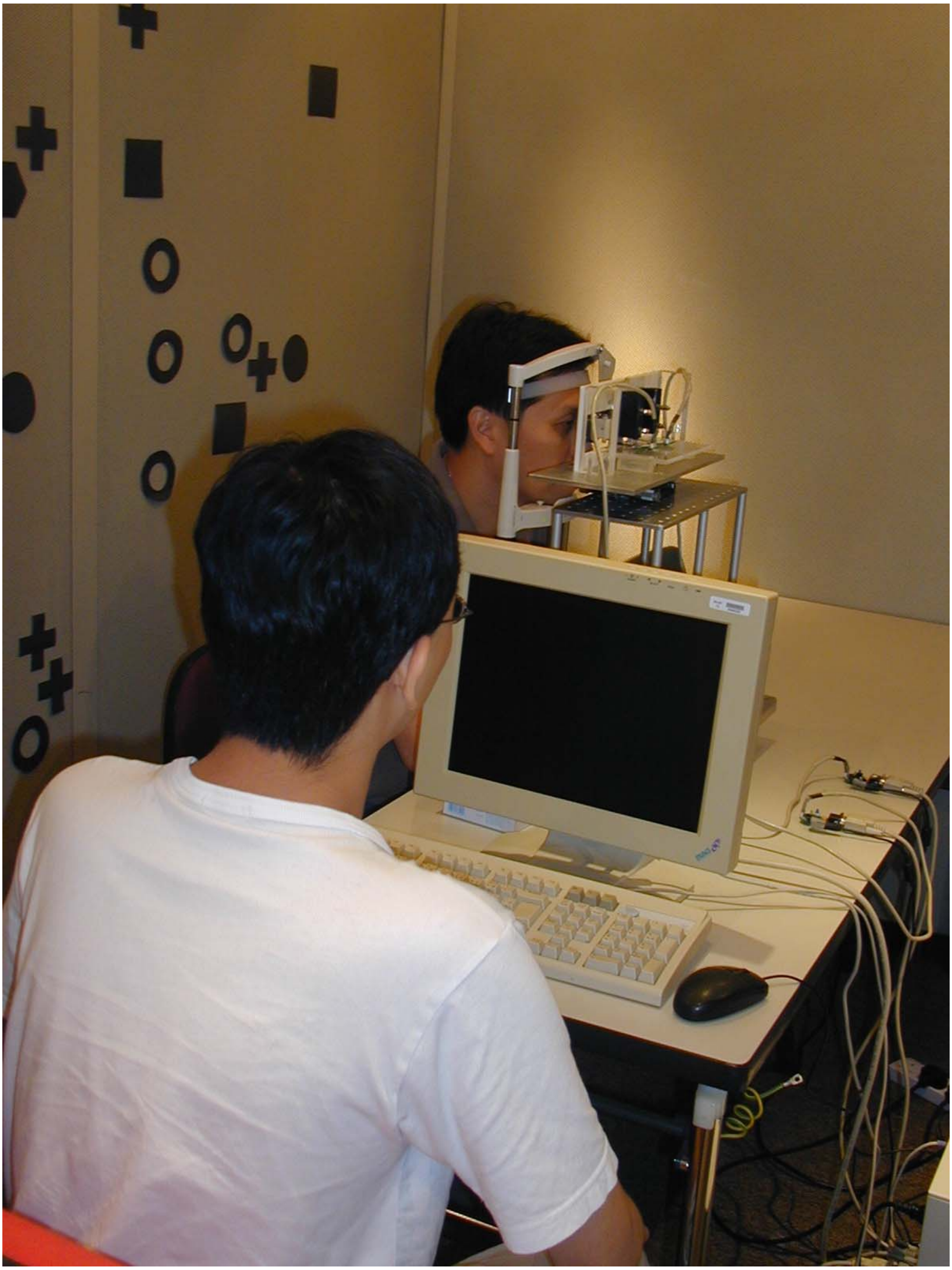

Figure 2.9 The layout of the experimental set-up. A computer screen was used by the experimenter to monitor the stimuli and the subject.

2.2.2 Stimuli

2.2.2.1 Task slides

A set of PowerPoint slides were presented to the eyes of subjects. Each slide consists of a group of five Landolt C rings viewed from left and right perspective combined together side-by-side. The left perspective view is for left eye viewing only and the right perspective view is for right eye viewing only. The five Landolt C rings are arranged in a cross shape manner. Figure 2.10 and 2.11 show examples of slide for stereo depth at 40cm and 200cm respectively.

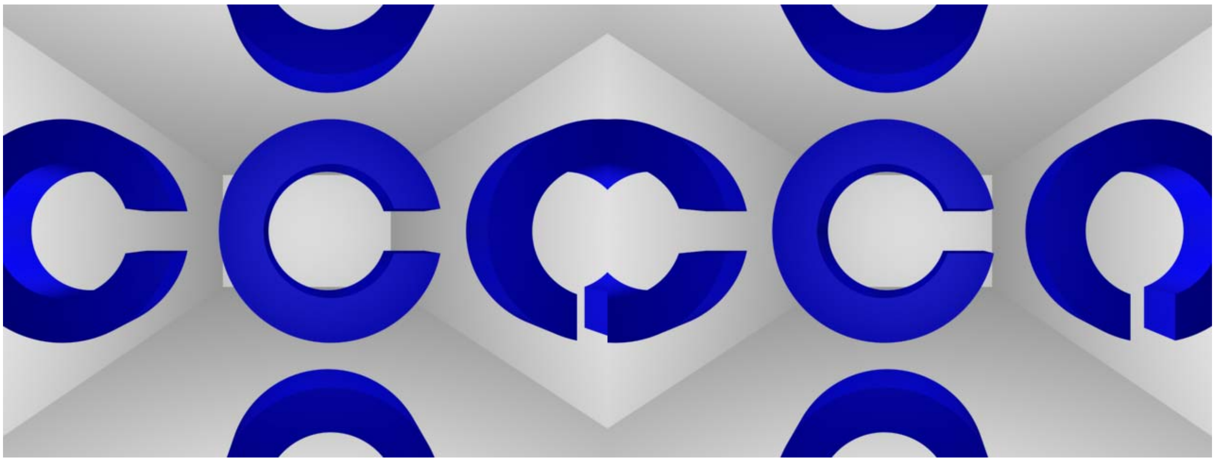

Figure 2.10 Snapshot of slide for stereo depth at 40cm. The left room is viewed by left eye only and the right room is viewed by right eye only.

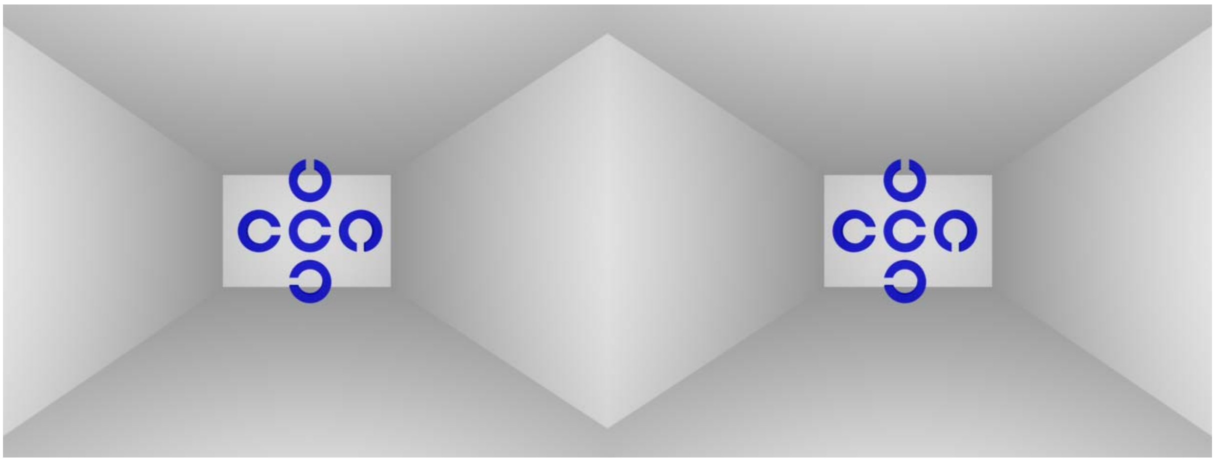

Figure 2.11 Snapshot of slide for stereo depth at 200cm. The left room is viewed by left eye only and the right room is viewed by right eye only.

The slides were created using 3D Studio Max™ Version 3.0. The outer radii of the Landolt C ring are 125 mm, the inner radii are 75 mm and the thicknesses are 50 mm. The widths of the openings of the Landolt C are 50 mm. The depth of the virtual room is 6000 mm, its width is 3000 mm and its height is 2000 mm. The Landolt C is blue in color and the virtual room is grey in color. Two cameras were used to create the left and right perspective view of the group of five Landolt C rings respectively.

2.2.2.2 Method of displaying the slides to the subject

When the slides are displayed and shown as PowerPoint presentation on computer in horizontal span mode, the image from left perspective will be displayed on the left LCD to the left eye. And the image from right perspective will be displayed on the right LCD to the right eye. When the subject sees the left and right images through the pair of lens, he/she will perceive a three-dimensional image at a certain stereo depth.

2.2.2.3 Method of changing the stereo depth

During the experiment, the stereo depth cues of Landolt C rings were changed by showing different PowerPoint slides so that their depths would be appropriate to either 40cm ±0.3 dioptres or 200cm ±0.3 dioptres.

Figure 2.12a to 2.12d shows an example of how the stereo depth cues are changed by presenting different slides to the eyes of subjects.

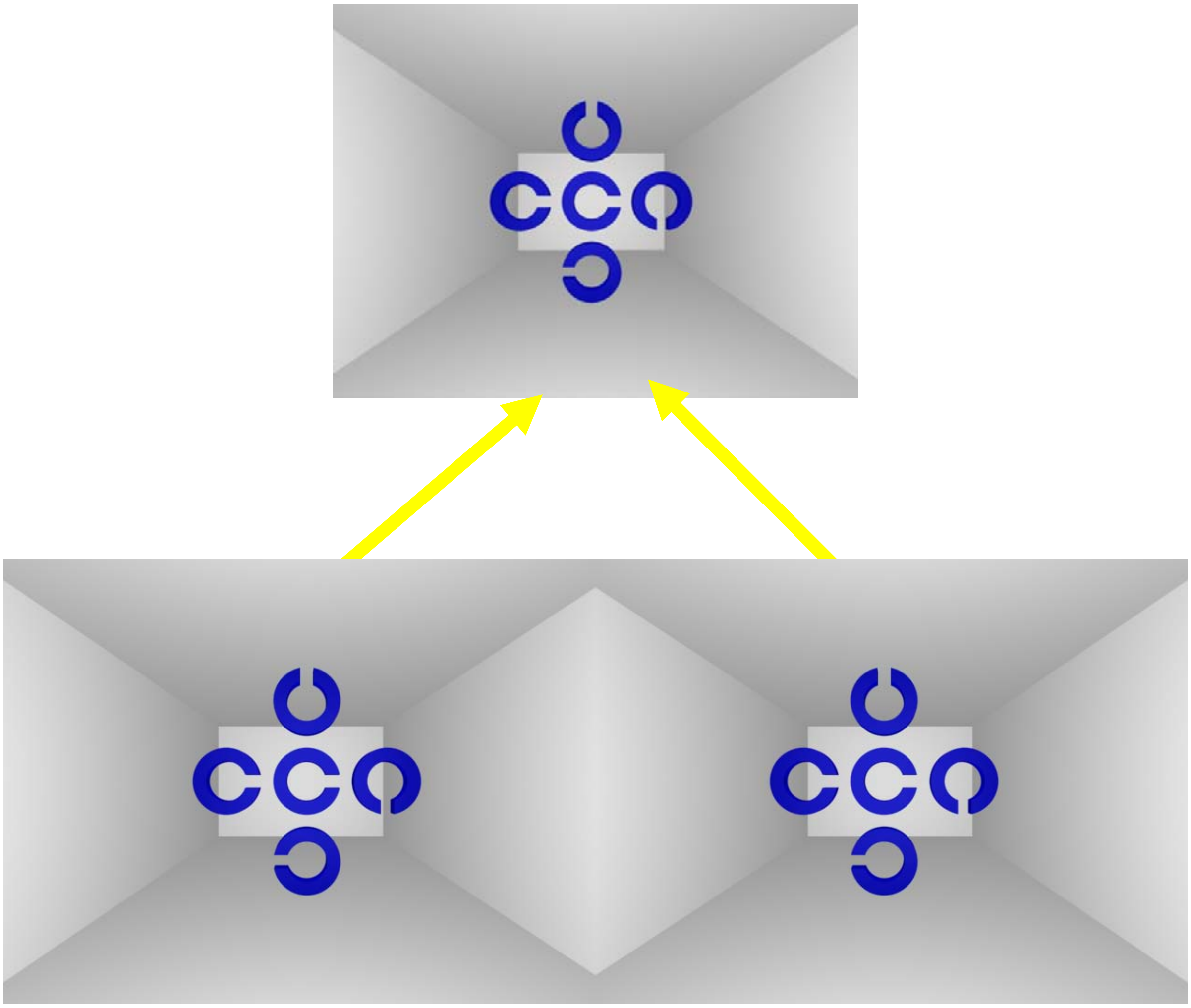

Figure 2.12a When the stereo pair slide as shown at the lower part of this figure is shown to the subject. The left eye of the subject will see the left room and the right eye will see the right room. The subject will perceive a single room with the Landolt C rings at a stereo depth of 125 cm (i.e. 200 cm – 0.3D) as shown on top of this figure.

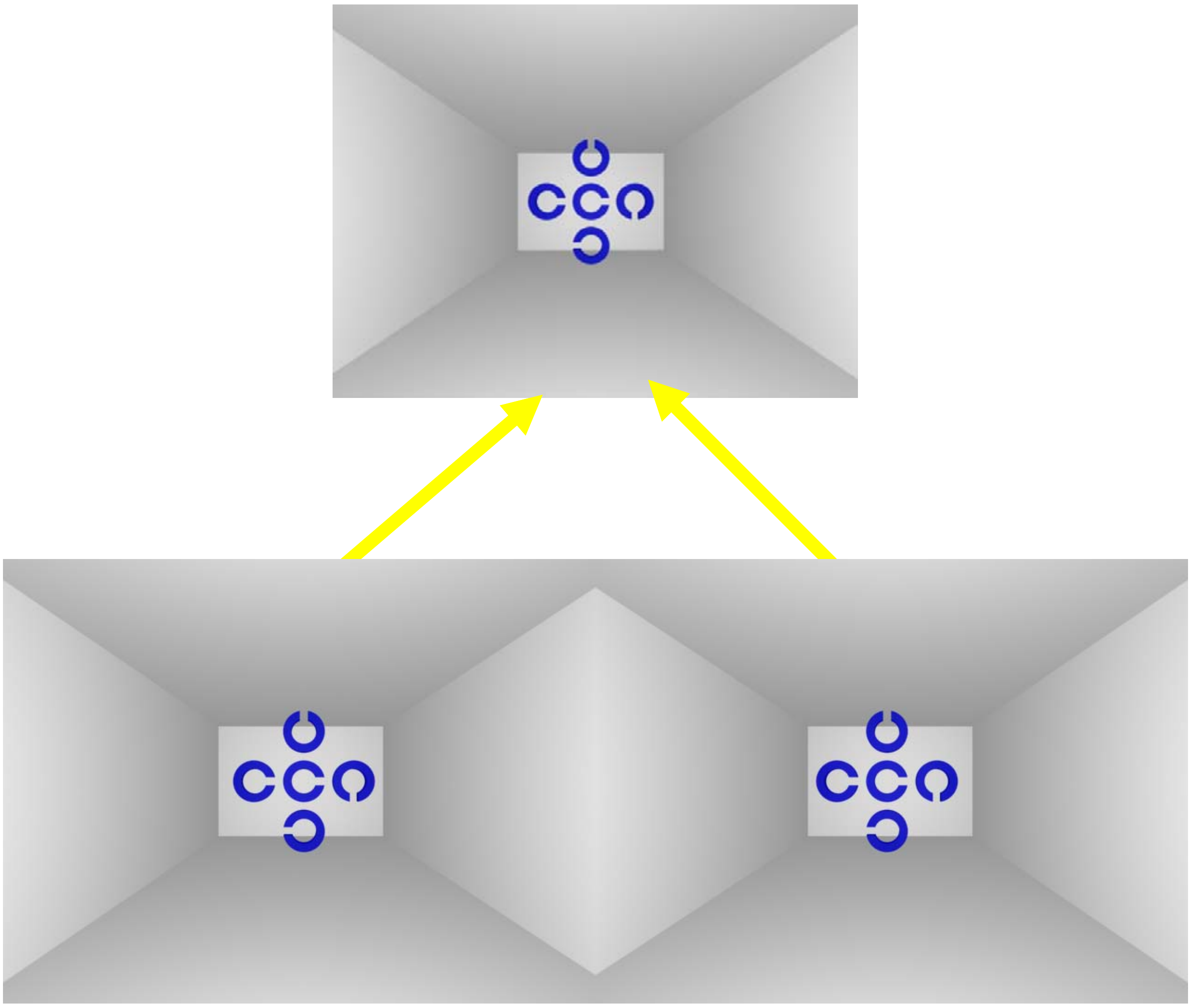

Figure 2.12b When the stereo pair slide as shown at the lower part of this figure is shown to the subject. The left eye of the subject will see the left room and the right eye will see the right room. The subject will perceive a single room with the Landolt C rings at a stereo depth of 200 cm as shown on top of this figure.

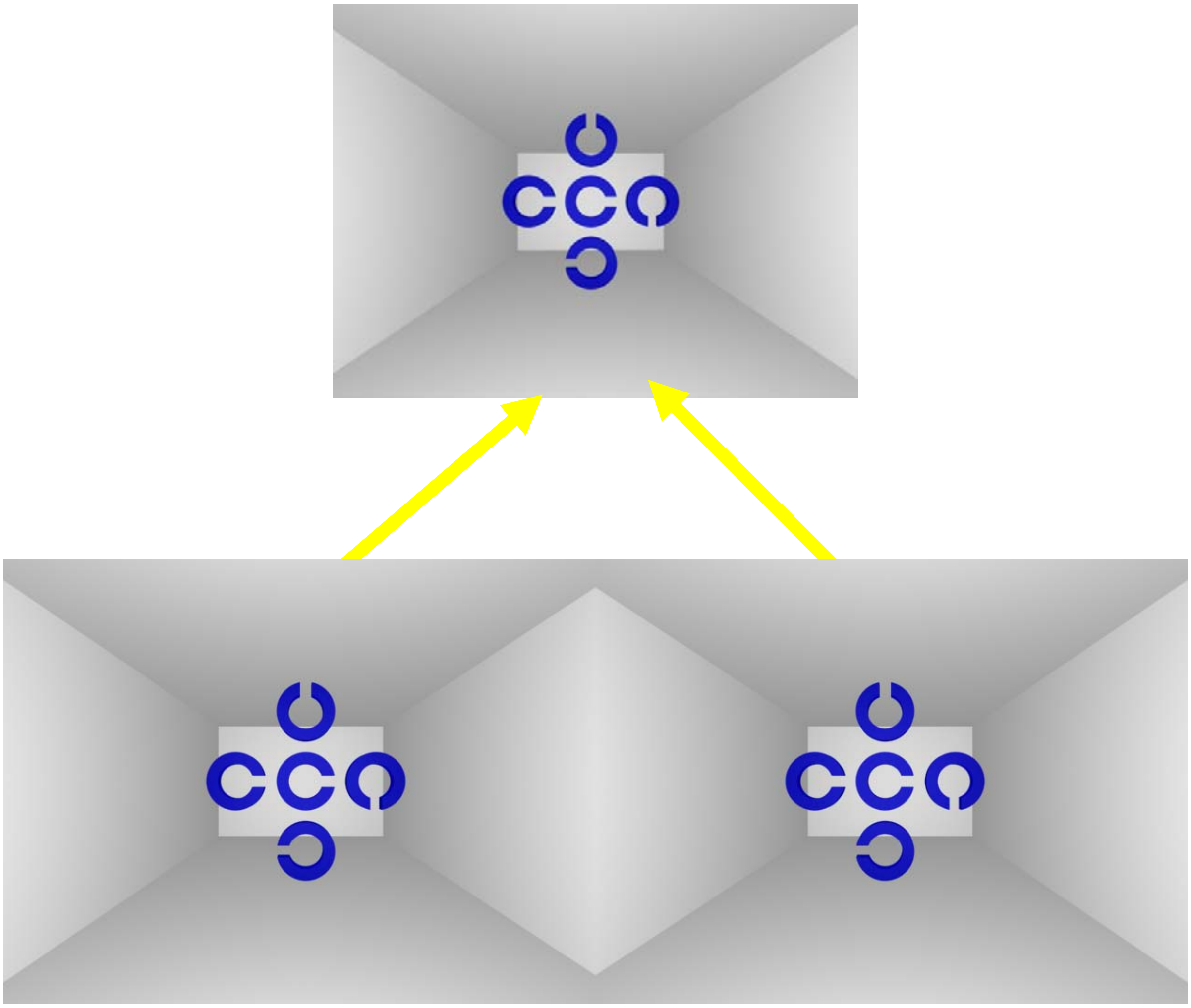

Figure 2.12c When the stereo pair slide as shown at the lower part of this figure is shown to the subject. The left eye of the subject will see the left room and the right eye will see the right room. The subject will perceive a single room with the Landolt C rings at a stereo depth of 143 cm (i.e. 200 cm – 0.2D) as shown on top of this figure.

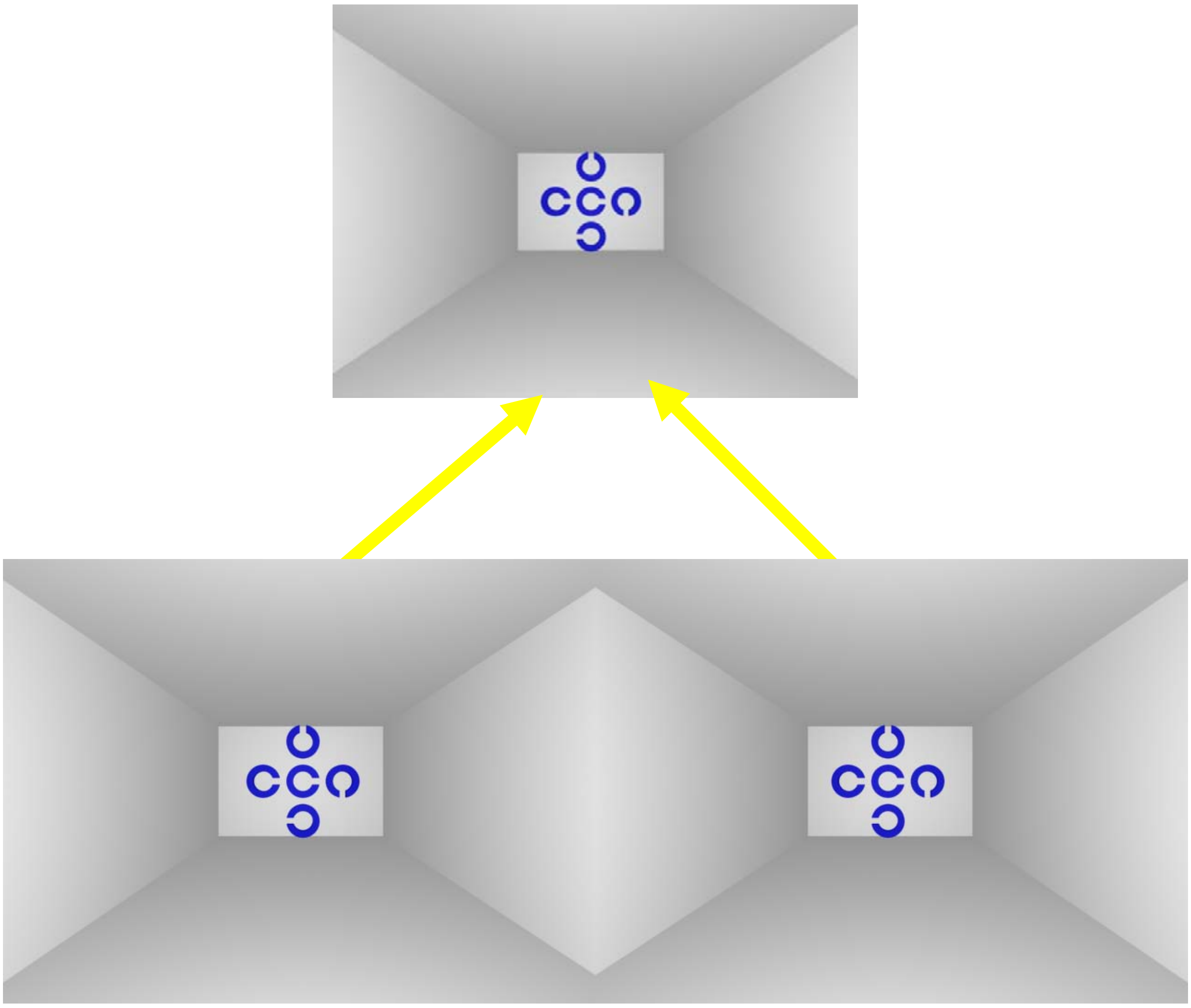

Figure 2.12d When the stereo pair slide as shown at the lower part of this figure is shown to the subject. The left eye of the subject will see the left room and the right eye will see the right room. The subject will perceive a single room with the Landolt C rings at a stereo depth of 250 cm (i.e. 200 cm + 0.1D) as shown on top of this figure.

In geometrical optics, distance expressed in dioptres (D) is defined as:

Dioptre (D) = 1 / distance (meter)

So, a distance of 1m corresponds to 1D and a distance of 10m corresponds to 0.1D.

For example, if stereo depth changes from 200cm to 200cm – 0.3D. In dioptres, it is equivalent to a stereo depth change from 0.5D to (0.5D – 0.3D = 0.2D). Convert back to distance in meter, the stereo depth changes from 2m to 5m. In centimeters, the stereo depth changes from 200 cm to 500 cm. So, the object would be farther away from the subject and the stereo depth has been changed by "– 0.3D" measured from 200cm.

Table 2.1 and 2.2 shows the stereo depths (in cm) and corresponding changes in stereo depth (in D) used in the experiment.

Table 2.1 Stereo depths used in the experiment which are varying within ±0.3D around 200cm.

Stereo Depth (cm)	**Stereo Depth change from 200cm (dioptres)**
125	+0.3D
143	+0.2D
167	+0.1D
200	0 D
250	-0.1D
333	-0.2D
500	-0.3D

Table 2.2 Stereo depths used in the experiment which are varying within ±0.3D around 40cm.

Stereo Depth (cm)	**Stereo Depth change from 40cm (dioptres)**
35.7	+0.3D
37	+0.2D
38.4	+0.1D
40	0 D
41.6	-0.1D
43.5	-0.2D
45.5	-0.3D

The range of varying the stereo depth is within the depth of focus and is consistent with previous study (±0.3 dioptres, Yano *et al*. 2004).

2.2.2.4 Stereo depth change sequence

The stereo depth of the Landolt C rings would change after a random period of five to seven seconds and variation in stereo depth (within ±0.3 dioptres) was also randomized so that subjects cannot predict when and how the stereo depth would be changed. A Visual C++ program was developed to automate this process. The program changes the stereo depth by changing the slide shown to the subject in every random period of five to seven seconds.

Figure 2.13 shows the time history of the change of stereo depth during the first 100 seconds of the experiment.

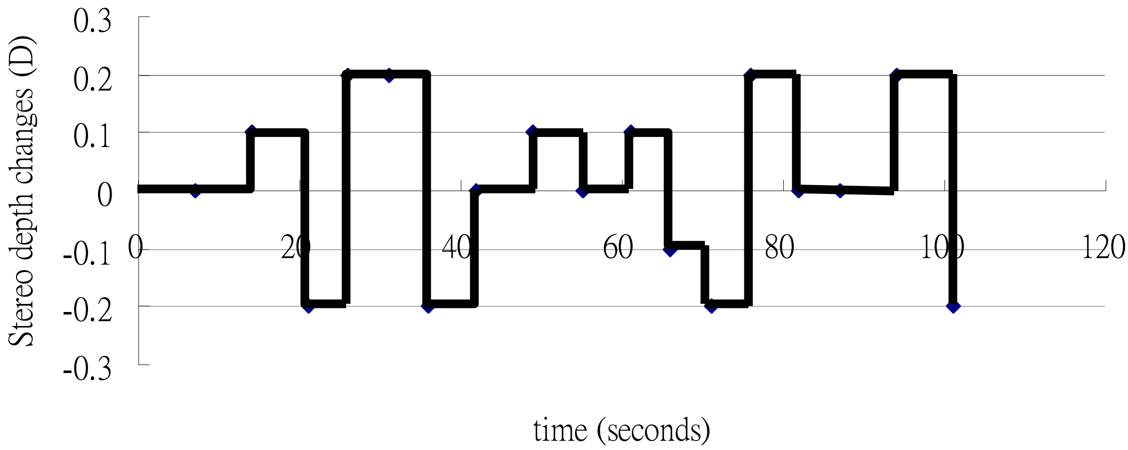

Figure 2.13 Time history of the change of stereo depth of the stereoscopic images during the first 100 seconds in the experiment. This stereo depth change sequence is the same for all four experimental conditions.

2.2.3 Tasks

During the experiment, subjects were required to read out the direction of the openings of the Landolt C rings at the middle of the Landolt C rings cross pattern (Figure 2.14). The directions of the opening of the Landolt C rings are randomized and independent of the stereo depth cues, so that the subjects did not have an educated guess on the directions of the opening of the Landolt C rings.

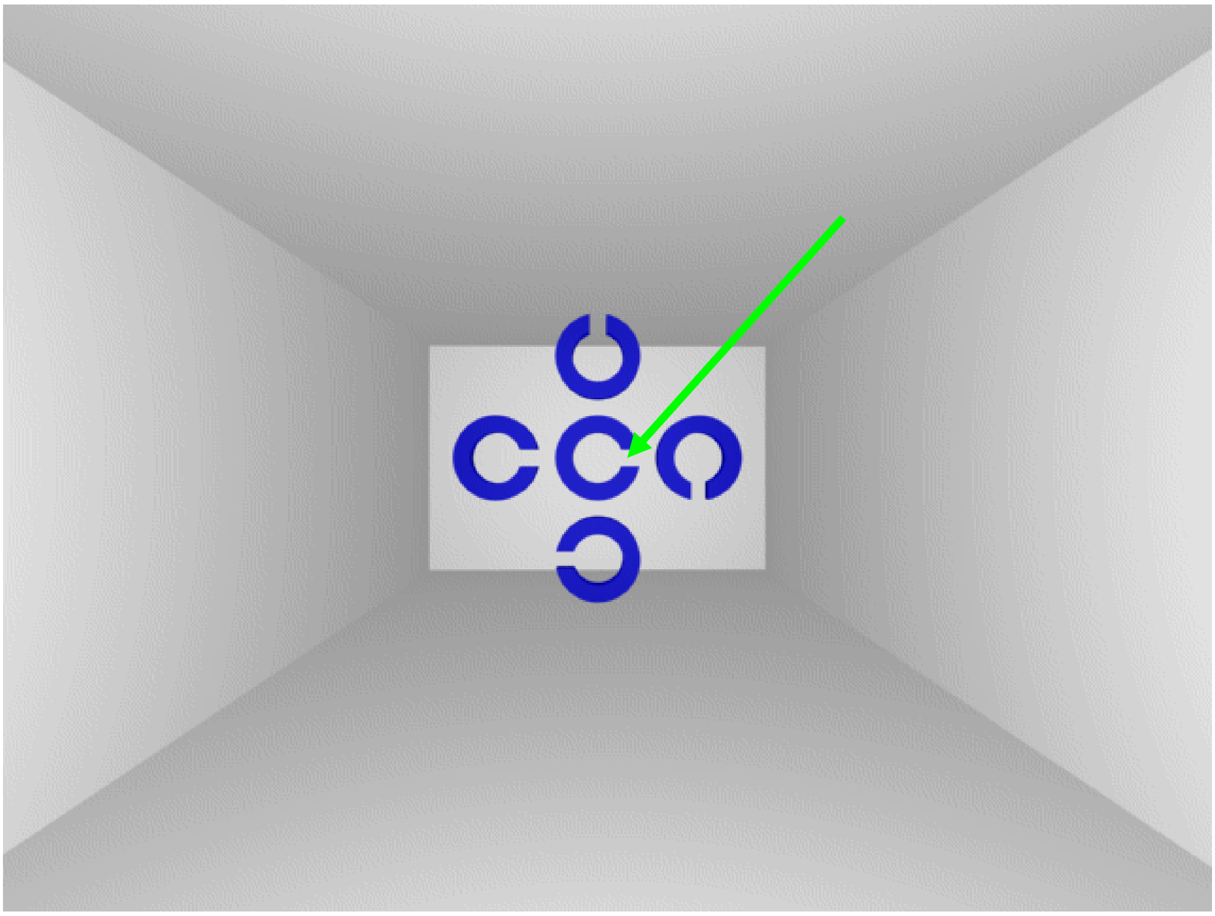

Figure 2.14 Subjects were required to read out the direction of the openings of the Landolt C rings at the middle of the Landolt C rings cross pattern (indicated by the arrow). In this case, subject should read “right” in the experiment when the corresponding stimulus slide was presented to the subject’s left eye and right eye.

2.2.4 Participants

There are fifteen subjects who had agreed to participate in the experiment in response to a mass recruitment email sent to the University community. However, three of them failed the pre-experiment screening test. Therefore, only twelve subjects had participated in the experiment. Nine of them are male and three of them are female. Their ages range from 20 to 45. All subjects had normal or corrected vision and they had been tested using a vision tester (Stereo Optical Co. Inc. Chicago, Illinois, U.S.A., Model: OPTEC2000) to have:

1. Far visual acuities with both eyes achieved 20/20 or better.

2. Near visual acuities with both eyes achieved 20/20 or better.
3. Stereoacuity better than or equal to 40 arc seconds.
4. Normal color discrimination ability.

All subjects are Chinese students or staffs at the university and the experiment has been approved by the Human Subject Committee of the Hong Kong University of Science and Technology.

2.2.5 Design of experiment

2.2.5.1 Independent variables

The independent variables are lens focus and stereoscopic depth cues. The lens focus has two levels: 40cm and 200cm. The stereoscopic depth cues also have two levels: stereo depth cues appropriate to a depth of 40cm ±0.3 dioptres and a depth of 200cm ±0.3 dioptres. The ±0.3 dioptres are within the normal range of depth of focus (DOF) (Wang & Ciuffreda. 2006). This two factor two level design derived four experimental conditions. Table 2.3 shows the classifications of the four conditions by the value of lens focus and stereo depth.

Table 2.3 Classifications of the four experimental conditions by the value of lens focus and stereo depth.

		Lens focus	
		40 cm	200 cm
Stereo depth	40 cm ± 0.3D	**Condition 1** Matched at 40 cm (Lens focus = Stereo depth)	**Condition 4** Mismatched (Lens focus > Stereo depth)
	200 cm ± 0.3D	**Condition 3** Mismatched (Lens focus < Stereo depth)	**Condition 2** Matched at 200 cm (Lens focus = Stereo depth)

2.2.5.2 Dependent variable

The dependent variable is a rated levels of eye fatigue measured using a 7-point eye fatigue rating scale. Readings are taken every 2 minutes during the exposure. Since, each experimental condition lasts for 30 minutes, 16 readings were taken in each condition for each subject. All subjects have to participate in all four experimental conditions, therefore the experiment is a kind of within-subject design. A total of 64 data points (16 readings x 4 conditions) were taken for each subject. Table 2.4 shows the definitions of the 7-point eye fatigue ratings.

Table 2.4 Definitions of 7-point eye fatigue ratings

0:	no symptom
1:	any unpleasant symptom related to my eyes, however slight
2:	mild unpleasant symptom related to my eyes
3:	mild tiredness related to my eyes
4:	mild to moderate tiredness related to my eyes
5:	moderate tiredness related to my eyes but can continue
6:	moderate tiredness related to my eyes, and want to stop

This 7-point eye fatigue ratings was adopted from a 7-point nausea ratings (Golding & Kerguelen. 1992, So, Lo & Ho. 2001) used in previous studies for investigating motion sickness caused by viewing real and simulated environment.

In the definition of 7-point eye fatigue ratings, "unpleasant symptom related to my eyes" can include any uncomfortable feelings to the subjects' eyes. Examples include: burning, irritation, tearing, and dryness located in the eyes. Therefore, the difference between ratings 2 and 3 is that rating 2 is not directly associated with eye fatigue while rating 3 is. A subject reported a fatigue rating of 3 indicates he/she start to feel fatigue in his/her eyes.

2.2.5.3 Control variables

The control variables are the randomized sequences of presentation of images with different stereo depth and the randomized time gap between the presentations of consecutive tasks. The experiment was conducted in acoustic room under complete darkness. The sound level inside the acoustic room was controlled at an average value of around 39.6dBA.

2.2.5.4 Design and conditions

The experiment had four conditions:

- Condition 1: lens focus was set at 40cm and stereo depth cues were appropriate to the depths of 40cm ± 0.3 dioptres. This is a matched condition where lens focus is equal to stereo depth.
- Condition 2: lens focus was set at 200cm and stereo depth cues were appropriate to the depths of 200cm ±0.3 dioptres. This is a matched condition where lens focus is equal to stereo depth.
- Condition 3: lens focus was set at 40cm and stereo depth cues were appropriate to the depths of 200cm ±0.3 dioptres. This is a mismatched condition where lens focus is smaller than stereo depth.
- Condition 4: lens focus was set at 200cm and stereo depth cues were appropriate to the depths of 40cm ±0.3 dioptres. This is a mismatched condition where lens focus is larger than stereo depth.

The experiment used a within-subject design and each subject took part in all four conditions in randomized order. At least 24 hours separation was given between each condition. Figure 2.15 shows an example of the presentation order of the four conditions.

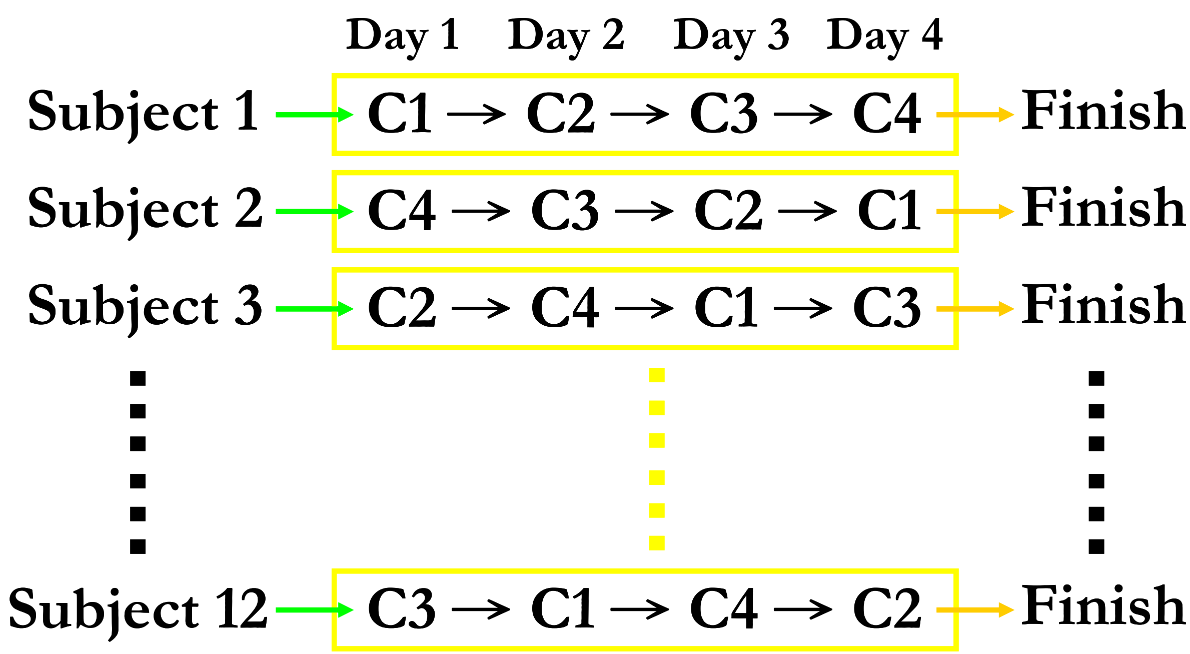

Figure 2.15 An example of the presentation order of the four conditions for different subjects. (Key: C1 = condition 1; C2 = condition 2; C3 = condition 3; C4 = condition 4)

2.2.5.5 Internal, Construct, and External Validities

2.2.5.5.1 Internal Validity

Internal validity concerns with how the study can provide sound reasons to support that the change in dependent variable is caused by independent variable, but not by other confounding variables. (McBurney, 1994).All subjects had performed a screen test before participating into the experiment to ensure they have no visual problems such as color blindness, poor visual acuity and poor stereoacuity that may lead to eye fatigue in certain conditions. This controls and minimizes any confounding effect(s) of color blindness, poor visual acuity, and poor stereoacuity on measured eye fatigue in this study.

If any subject report non-zero eye fatigue rating at the start of the experiment, they would be asked to rest for 10 minutes and if the fatigue remained, they would be asked to come back at another day. This ensures that all subjects will start from eye fatigue level 0 (i.e. no symptom). This indicates that all subjects report no eye fatigue before the experiment.

Such a control measure ensures that the eye fatigue measured in the experiment should be caused by the experimental treatment(s) rather than the source(s) outside the lab.

Since the presentation order of conditions was randomized, therefore, the results observed could not be attributed to learning effect or adaptation effect across the conditions. On top of that correlation test on presentation order of conditions versus eye fatigue level could be conducted to verify whether learning effect is present. Indeed, a test of correlation between the order of presentation and the average levels of eye fatigue indicates non-significant relationship ($p>0.5$, Spearman correlation test).

Because the incompatibility between the lens focus and the stereo depth are results from factorial combinations of lens focus and stereo depth, inevitably, the effects of compatibility (between lens focus and stereo depth) are confounded with either the effects of accommodation (i.e., lens focus) or the effects of stereo depth. In order to systematically analyze the effects of compatibility, data from corresponding pair of conditions are compared so that the effects of compatibility are analyzed under the following four confounding situations:

(i) when lens focus is controlled at 40cm, the effects of compatibility is confounded with the effects of stereo depth (hypothesis H1);

(ii) when lens focus is controlled at 200cm, the effects of compatibility is confounded with the effects of stereo depth (hypothesis H2);

(iii) when stereo depth is controlled at 40cm, the effects of compatibility is confounded with the effects of accommodation (hypothesis H3); and

(iv) when stereo depth is controlled at 200cm, the effects of compatibility is confounded with the effects of accommodation (hypothesis H4).

Because most virtual reality applications present stereoscopic images to users with size matched with stereo depth cues. Therefore, in order to present a closer to natural viewing situation and to make the result more applicable to virtual reality industries, the size of the target (i.e. Landolt C rings) changes with the stereo depth cues. As a result, the effect from stereo depth cues is confounded with the effect from apparent size. In fact, results indicate that apparent size is not a dominant factor to the eye fatigue. (see section 3.4 for details).

2.2.5.5.2 Construct Validity

Construct validity concerns with whether the results can support the theory behind the study, rather than other theories. (McBurney, 1994). The underlying theory behind the hypotheses to be tested in this study is that the pro-longed inappropriate convergence demands will cause increases in eye fatigue. During the experiment, participants were instructed to fuse stereo images of Landolt C rings and were required to read out the directions of opening of Landolt C rings. Similar stereo fusion tasks have been used in previous studies to measure fusion time of stereo images (Wong, 2007). .

Participants were only told that their eye fatigue levels were measured. They were not informed about the objectives and hypotheses of the experiment in case they have subjective biases..

2.2.5.5.3 External Validity

External validity concerns with how well the results of a study apply to other situations or populations. (McBurney, 1994). All participants were volunteers randomly recruited. They are Chinese students or staffs at HKUST and have been screened to have attained normal visual acuity and stereoacuity. The use of Landolt C rings in the stereo fusion task reduce the influence of culture and language factors. Statistics are used to quantify the chances of repeating the results. The apparatus used in this study have been used in previous studies on stereo fusion times (Wong, 2007).

2.2.5.6 Procedure

2.2.5.6.1 Before the experiment

The lens focus was adjusted to the suitable level according to the condition required. The Landolt C rings cross pattern PowerPoint slide with stereo depth cue appropriate to the condition was shown on the LCD. The distance between the optical axes of the two lenses was adjusted to suit the subject's inter-pupillary distance (IPD).

The experiment procedure was explained to the subject and the subject had agreed to participate in the experiment by signing the subject consent form. Then, the subject was instructed to look at the task stimuli through the pair of lens to ensure he/she can form a single stereoscopic image of the Landolt C rings cross pattern. If the subject can form a single stereoscopic image successfully, he/she was instructed to sit there without looking the stimuli and wait until the experimenter signal the start of the experiment. Subject could start to see the stimuli through the pair of lens again after the experimenter had signaled the start of the experiment.

2.2.5.6.2 During the experiment

The stereo depth cues of the Landolt C rings cross pattern and the direction of openings of the C rings were changing. The subject was required to concentrate on the stereo images and verbally reported the direction of the openings of the one Landolt C which is located at the middle of the cross pattern to ensure he/she is viewing the stereo image.

Each experiment lasted for 30 minutes and was conducted in complete darkness environment. The subject was required to rate his/her level of eye fatigue according to a 7-point eye fatigue rating during the experiment. These rated levels were taken every two minutes. So, a total of 16 eye fatigue data points for this subject in one condition were recorded during this 30 minutes interval.

2.2.5.6.3 After the experiment

At least 24 hours separation was given before the subjects return for another condition in another day to allow subject to take rest.

2.3 Results

2.3.1 Overview

Figure 2.16 shows the averaged eye fatigue level for the four conditions. The averaged eye fatigue level for one condition is calculated by averaging the 192 eye fatigue level data points (16 data points per subject x 12 subjects = 192 data points) in that condition.

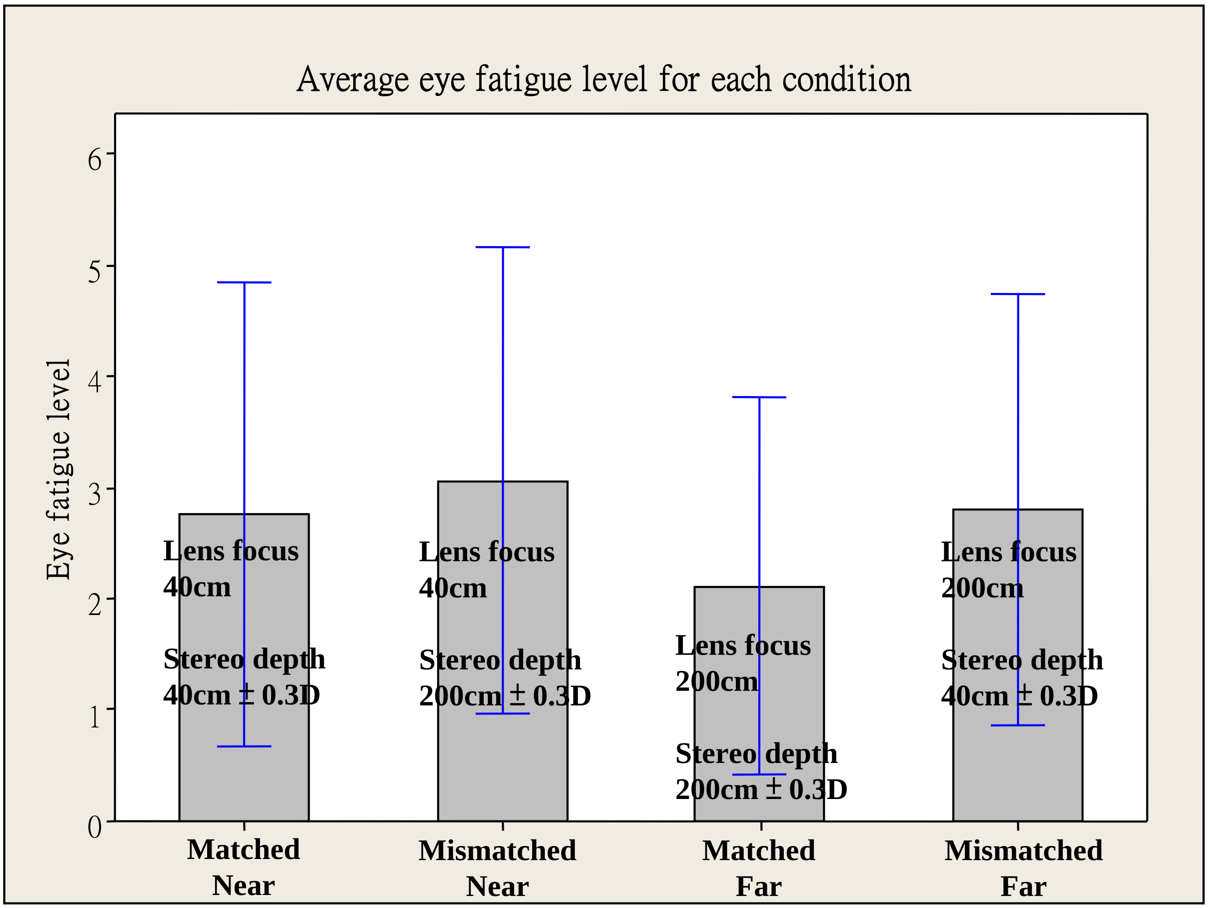

Figure 2.16 Averaged eye fatigue level of the 12 subjects under the 4 viewing conditions.

It can be seen from figure 2.16 that the condition where lens focus is 200 cm and stereo depth at 200 cm ± 0.3D produces the least amount of average eye fatigue level. The next lowest is the condition where lens focus is 40 cm and stereo depth at 40 cm ± 0.3D. Statistical tests are conducted to find out if there are any differences among these conditions.

2.3.2 Results of ANOVAs

ANOVA is conducted to study the effect of lens focus and stereo depth on the eye fatigue level. The assumptions of ANOVA are normality, constant variance and independence of the data. So the normality of the data (consisted of 768 data points) is examined by using normality plot and Shapiro-Wilk test.

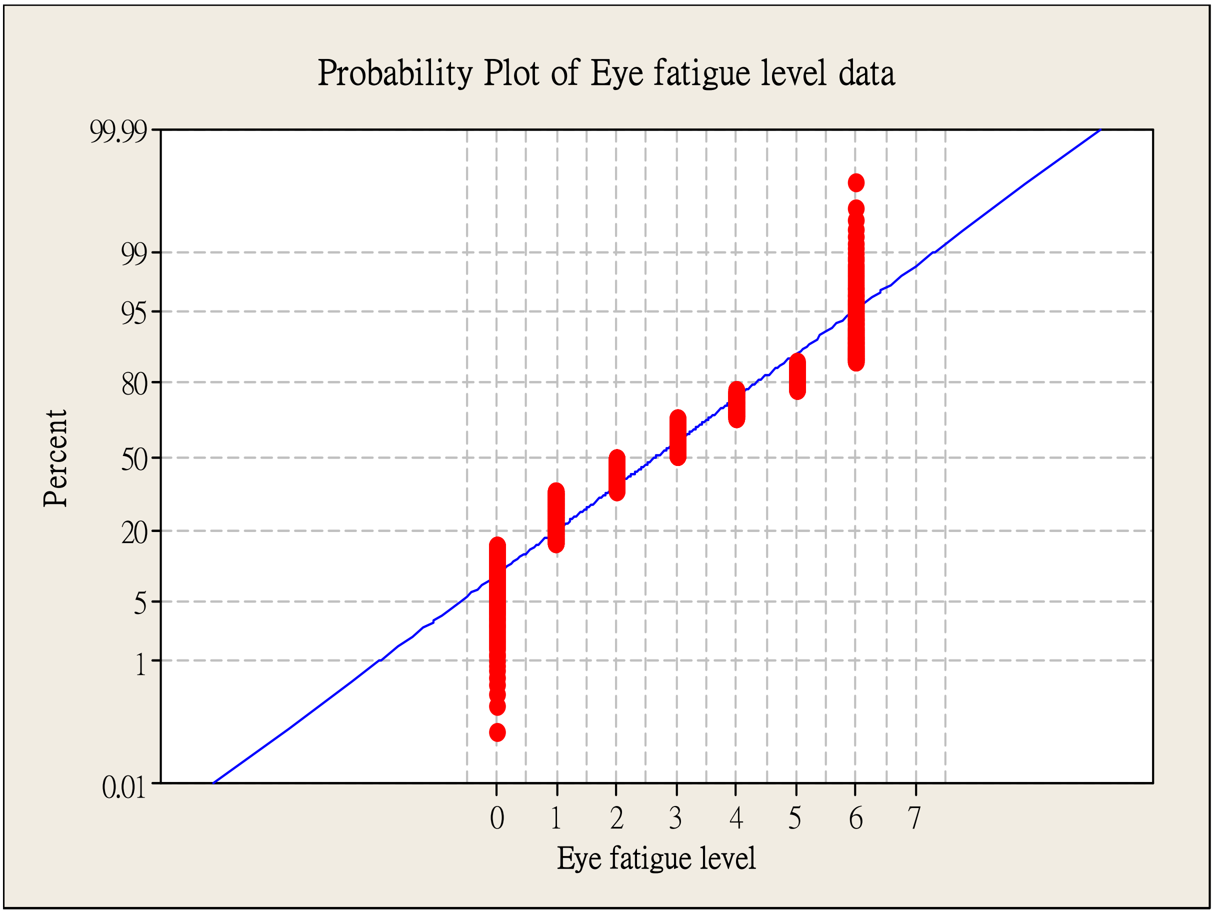

Figure 2.17 Normal probability plot of the eye fatigue level data.

Inspection of figure 2.17 indicated that the data did not satisfy the normality criteria because the data did not form a straight line. In addition, results of the Shapiro-Wilk test indicated that W is 0.910048 (p<0.0001). Consequently, the data should be transformed so as to improve its normality.

Box-Cox transformation is used to transform the data. The relationships between the transformed data and the original data are:

transformed data = (data + 1)^(λ) when λ is not zero.

transformed data = ln(data + 1) when λ is zero. (Remark: ln stands for natural logarithm)

A value of 1 is added to all original data because some data has a value of 0 and box-cox transformation cannot be applied to data with zero or negative value.

SAS (Release 8.02) is used to recommend the lambda value (λ) and the suggested best value of λ by SAS for the 768 data points is 0.5

Box-cox transformation is applied to the data with λ = 0.5 and the normal plot of the transformed data is shown in figure 2.18.

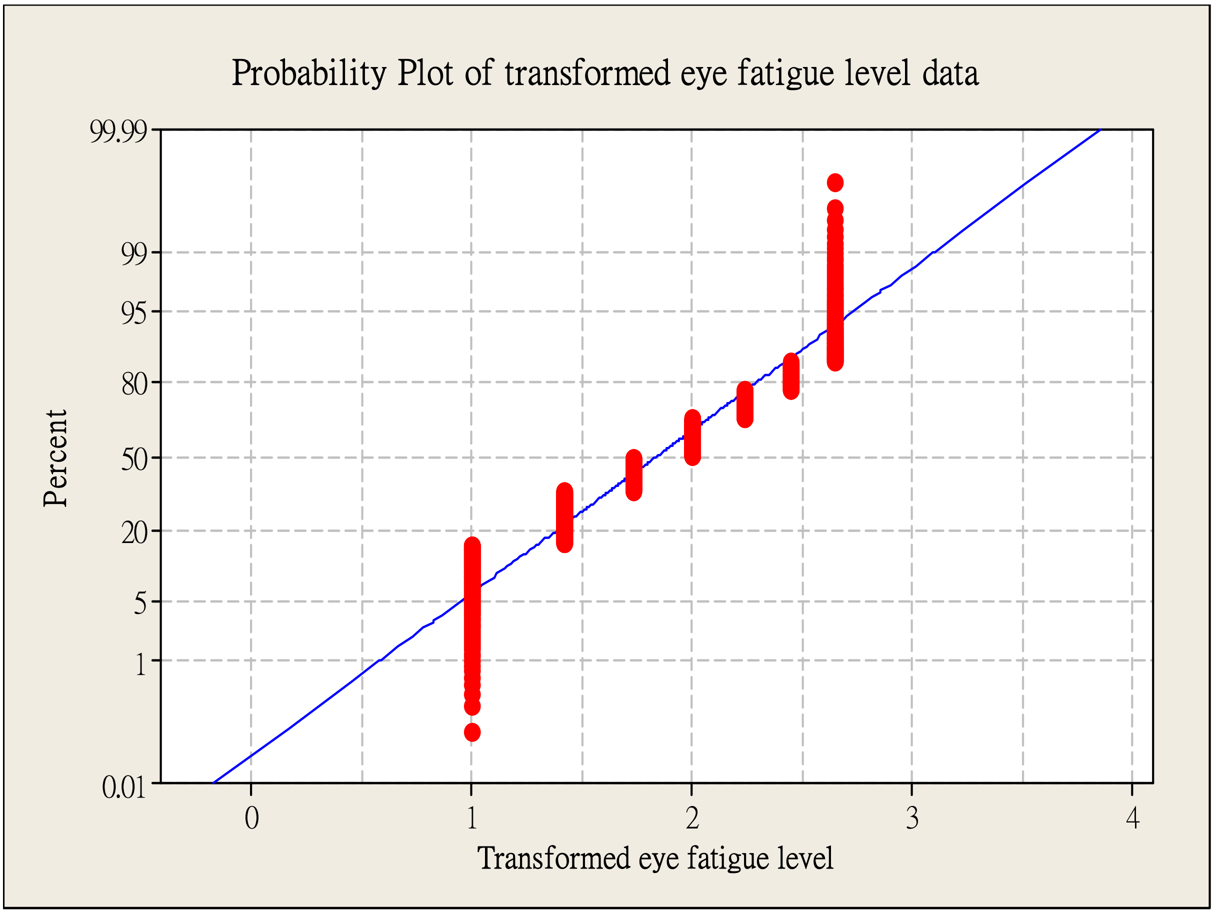

Figure 2.18 Normal probability plot of the box-cox transformed eye fatigue level data.

The normality plot in figure 2.18 of the 768 transformed data points showed that the normality of the data is not improved. In the Shapiro-Wilk test, the W value is 0.919815 but the *p* value is still smaller than 0.0001. The Shapiro-Wilk test did not support the normality of the transformed data.

Since after data transformation the data still could not satisfy the assumptions of ANOVA, all the significant results obtained by ANOVA are verified by nonparametric tests.

The ANOVA of the transformed data is shown in table 2.5. The ANOVA result indicates that: lens focus, stereo depth, the duration of the experiment, age of subjects, the interaction between lens focus and stereo depth has significant effects on the eye fatigue level (p <0.005).

Table 2.5 ANOVA of the transformed eye fatigue level data.

Dependent Variable: Eye fatigue level (Box-Cox transformed, lambda = 0.5)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	66	179.0629614	2.7130752	42.07	<.0001
Error	701	45.2079114	0.0644906		
Corrected Total	767	224.2708728			

R-Square	Coeff Var	Root MSE	Mean
0.798423	13.79212	0.253950	1.841269

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Lensfocus	1	2.2369912	2.2369912	34.69	<.0001
StereoDepth	1	0.4801491	0.4801491	7.45	0.0065
Duration	15	146.6257259	9.7750484	151.57	<.0001
Age	6	19.9601203	3.3266867	51.58	<.0001
Lensfocus*StereoDepth	1	3.1297796	3.1297796	48.53	<.0001
Lensfocus*Duration	15	0.7509953	0.0500664	0.78	0.7049
StereoDepth*Duration	15	0.2301712	0.0153447	0.24	0.9988
Lensfocus*Age	6	3.4355292	0.5725882	8.88	<.0001
StereoDepth*Age	6	2.2134995	0.3689166	5.72	<.0001

The ANOVA result also indicates that: the interaction between age and lens focus, the interaction between age and stereo depth has significant effects on the eye fatigue level ($p < 0.0001$). However it is found that there is no correlation between age and eye fatigue. Also, the interaction plots did not suggest a meaningful relationship between age and lens focus as well as age and stereo depth. Therefore the age, the interaction between age and lens focus, the interaction between age and stereo depth are taken out from the ANOVA model. See Appendix B for details.

The ANOVA of the transformed data with the age factor taken out is shown in table 2.6. The ANOVA result indicates that: lens focus, stereo depth, the duration of the experiment and the interaction between lens focus and stereo depth has significant effects on the eye fatigue level ($p < 0.05$).

Table 2.6 ANOVA of the transformed eye fatigue level data with the age factor and its two-way interaction with lens focus, image depth being taken out.

Dependent Variable: Eye fatigue level (Box-Cox transformed, lambda = 0.5)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	48	153.4538124	3.1969544	32.46	<.0001
Error	719	70.8170605	0.0984938		
Corrected Total	767	224.2708728			

R-Square	Coeff Var	Root MSE	Tire Mean
0.684234	17.04462	0.313837	1.841269

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Lensfocus	1	2.2369912	2.2369912	22.71	<.0001
StereoDepth	1	0.4801491	0.4801491	4.87	0.0276
Duration	15	146.6257259	9.7750484	99.25	<.0001
Lensfocus*StereoDepth	1	3.1297796	3.1297796	31.78	<.0001
Lensfocus*Duration	15	0.7509953	0.0500664	0.51	0.9369
StereoDepth*Duration	15	0.2301712	0.0153447	0.16	0.9999

2.3.3 Testing of hypotheses

2.3.3.1 Testing of hypothesis H1

The hypothesis H1 is repeated below for convenience:

At lens focus 40cm, the eye fatigue level at stereo depth 40cm ± 0.3D (a matched condition C1) will be significantly lower than that of at stereo depth 200cm ± 0.3D (a mismatched condition C3).

ANOVA is performed on data taken from condition 1 (lens focus at 40cm, stereo depth at 40cm ± 0.3D; 192 data points) and condition 3 (lens focus at 40cm, stereo depth at 200cm ± 0.3D; 192 data points). The result is shown in table 2.7.

Table 2.7 Result of ANOVA for eye fatigue level under conditions 1 and 3.

Dependent Variable: Eye fatigue level (Box-Cox transformed, lambda = 0.5)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	31	83.8002256	2.7032331	25.11	<.0001
Error	352	37.8981778	0.1076653		
Corrected Total	383	121.6984034			

R-Square	Coeff Var	Root MSE	Tire Mean
0.688589	17.31306	0.328124	1.895239

Source	DF	Anova SS	Mean Square	F Value	Pr > F
StereoDepth	1	0.57909286	0.57909286	5.38	0.0210
Duration	15	82.91263036	5.52750869	51.34	<.0001
StereoDepth*Duration	15	0.30850236	0.02056682	0.19	0.9997

Result from ANOVA indicates that duration is a significant factor ($F_{15,383} = 51.34$; $p < 0.0001$). When lens focus was fixed at 40cm, stereo depth is also a significant factor ($F_{1,383} = 5.38$; $p = 0.021$). However, Wilcoxon signed-rank test of averaged eye fatigue level over 30 minutes for 12 subjects, which compared condition 1 with condition 3, didn't support that stereo depth is a significant factor ($p = 0.125$). Therefore, H1 is not supported.

2.3.3.2 Testing of hypothesis H2

The hypothesis H2 is repeated below for convenience:

At lens focus 200cm, the eye fatigue level at stereo depth 200cm ± 0.3D (a matched condition C2) will be significantly lower than that of at stereo depth 40cm ± 0.3D (a mismatched condition C4).

ANOVA is performed on data taken from condition 2 (lens focus at 200cm, stereo depth at 200cm ± 0.3D; 192 data points) and condition 4 (lens focus at 200cm, stereo depth at 40cm ± 0.3D; 192 data points). The result is shown in table 2.8.

Table 2.8 Result of ANOVA for eye fatigue level under conditions 2 and 4.

Dependent Variable: Eye fatigue level (Box-Cox transformed, lambda = 0.5)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	31	68.0009675	2.1935796	23.88	<.0001
Error	352	32.3345108	0.0918594		
Corrected Total	383	100.3354782			

R-Square	Coeff Var	Root MSE	Tire Mean
0.677736	16.95761	0.303083	1.787299

Source	DF	Anova SS	Mean Square	F Value	Pr > F
StereoDepth	1	3.03083588	3.03083588	32.99	<.0001
Duration	15	64.46409087	4.29760606	46.78	<.0001
StereoDepth*Duration	15	0.50604072	0.03373605	0.37	0.9861

Result from ANOVA indicates that duration is a significant factor ($F_{15,383} = 46.78$; $p < 0.0001$). When lens focus was fixed at 200cm, stereo depth is also a significant factor ($F_{1,383} = 32.99$; $p < 0.0001$). Wilcoxon signed-rank test of averaged eye fatigue level over 30 minutes for 12 subjects, which compared condition 2 with condition 4, also supported that stereo depth is a significant factor (p = 0.041). Therefore, H2 is supported.

2.3.3.3 Testing of hypothesis H3

The hypothesis H3 is repeated below for convenience:

At stereo depth 40cm ± 0.3D, the eye fatigue level at lens focus 40cm (a matched condition C1) will be significantly lower than that of at lens focus 200cm (a mismatched condition C4).

ANOVA is performed on data taken from condition 1 (lens focus at 40cm, stereo depth at 40cm ± 0.3D; 192 data points) and condition 4 (lens focus at 200cm, stereo depth at 40cm ± 0.3D; 192 data points). The result is shown in table 2.9.

Table 2.9 Result of ANOVA for eye fatigue level under conditions 1 and 4.

Dependent Variable: Eye fatigue level (Box-Cox transformed, lambda = 0.5)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	31	77.1326005	2.4881484	24.06	<.0001
Error	352	36.4049013	0.1034230		
Corrected Total	383	113.5375017			

R-Square	Coeff Var	Root MSE	Tire Mean
0.679358	17.23191	0.321594	1.866273

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Lensfocus	1	0.03739042	0.03739042	0.36	0.5480
Duration	15	76.82843643	5.12189576	49.52	<.0001
Lensfocus*Duration	15	0.26677361	0.01778491	0.17	0.9998

Result from ANOVA indicates that duration is a significant factor ($F_{15,383} = 49.52$; p <0.0001). When stereo depth was changing within 40cm ± 0.3D, lens focus is not a significant factor ($F_{1,383} = 0.36$; $p = 0.548$). Wilcoxon signed-rank test of averaged eye fatigue level over 30 minutes for 12 subjects, which compared condition 1 with condition 4, also didn't support that lens focus is a significant factor ($p = 0.9868$). Therefore, H3 is not supported.

2.3.3.4 Testing of hypothesis H4

The hypothesis H4 is repeated below for convenience:

At stereo depth 200cm ± 0.3D, the eye fatigue level at lens focus 200cm (a matched condition C2) will be significantly lower than that of at lens focus 40cm (a mismatched condition C3).

ANOVA is performed on data taken from condition 2 (lens focus at 200cm, stereo depth at 200cm ± 0.3D; 192 data points) and condition 3 (lens focus at 40cm, stereo depth at 200cm ± 0.3D; 192 data points). The result is shown in table 2.10.

Table 2.10 Result of ANOVA for eye fatigue level under conditions 2 and 3.

Dependent Variable: Eye fatigue level (Box-Cox transformed, lambda = 0.5)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	31	76.4254347	2.4653366	25.65	<.0001
Error	352	33.8277873	0.0961017		
Corrected Total	383	110.2532220			

R-Square	Coeff Var	Root MSE	Tire Mean
0.693181	17.06814	0.310003	1.816265

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Lensfocus	1	5.32938039	5.32938039	55.46	<.0001
Duration	15	70.02746067	4.66849738	48.58	<.0001
Lensfocus*Duration	15	1.06859361	0.07123957	0.74	0.7420

Result from ANOVA indicates that duration is a significant factor ($F_{15,383} = 48.58$; $p < 0.0001$). When stereo depth was changing within 200cm ± 0.3D, lens focus is a significant factor ($F_{1,383} = 55.46$; $p < 0.0001$). Wilcoxon signed-rank test of averaged eye fatigue level over 30 minutes for 12 subjects, which compared condition 2 with condition 3, also supported that lens focus is a significant factor ($p = 0.0205$). Therefore, H4 is supported.

CHAPTER 3

GENERAL DISCUSSION

3.1 Effects of accommodation (lens focus), vergence (stereo depth), and matching (two-way interaction)

Figure 3.1 summarizes the results from the test of the four hypotheses described in Section 2.3.3. Inspections of Figure 3.1 indicate that when lens focus is set at 200cm, eye fatigue resulted from viewing images with stereo depth cues appropriate to 200cm is significantly lower than those resulted from viewing images with stereo depth cues appropriate to 40cm. This demonstrates that the inappropriate matching of lens focus and stereo depth can lead to significant increases in eye fatigue. This finding is of special importance to HMD manufacturers who fixed the lens focus of their HMDs as 200cm (e.g., iMD Ltd.). The natural solution to the increased eye fatigue is to adjust the lens focus to match with the stereo depth. Unfortunately, setting lens focus at 40cm to match with images of stereo depth cues appropriate to 40cm did not result into reduced eye fatigue level. It seems like matching cannot provide us with hypothetical benefits of reduced eye fatigue level. Referring back to section 2.2.5.5.1 about internal validity, the effects of matching (interaction between lens focus and stereo depth) are inevitably confounded with either the effects of accommodation (i.e., lens focus) or the effects of vergence (stereo depth). That is, the matching effect may not be the only effect that comes into play. In this case, with the stereo depth controlled at 40cm, adjusting the lens focus from 200cm to 40cm can reduce the rated levels of eye fatigue due to mismatch, however, the confounding effects of change accommodate from far to near will increase the eye fatigue. As a result, the benefit from matching is being offset by detrimental effects of near accommodation.

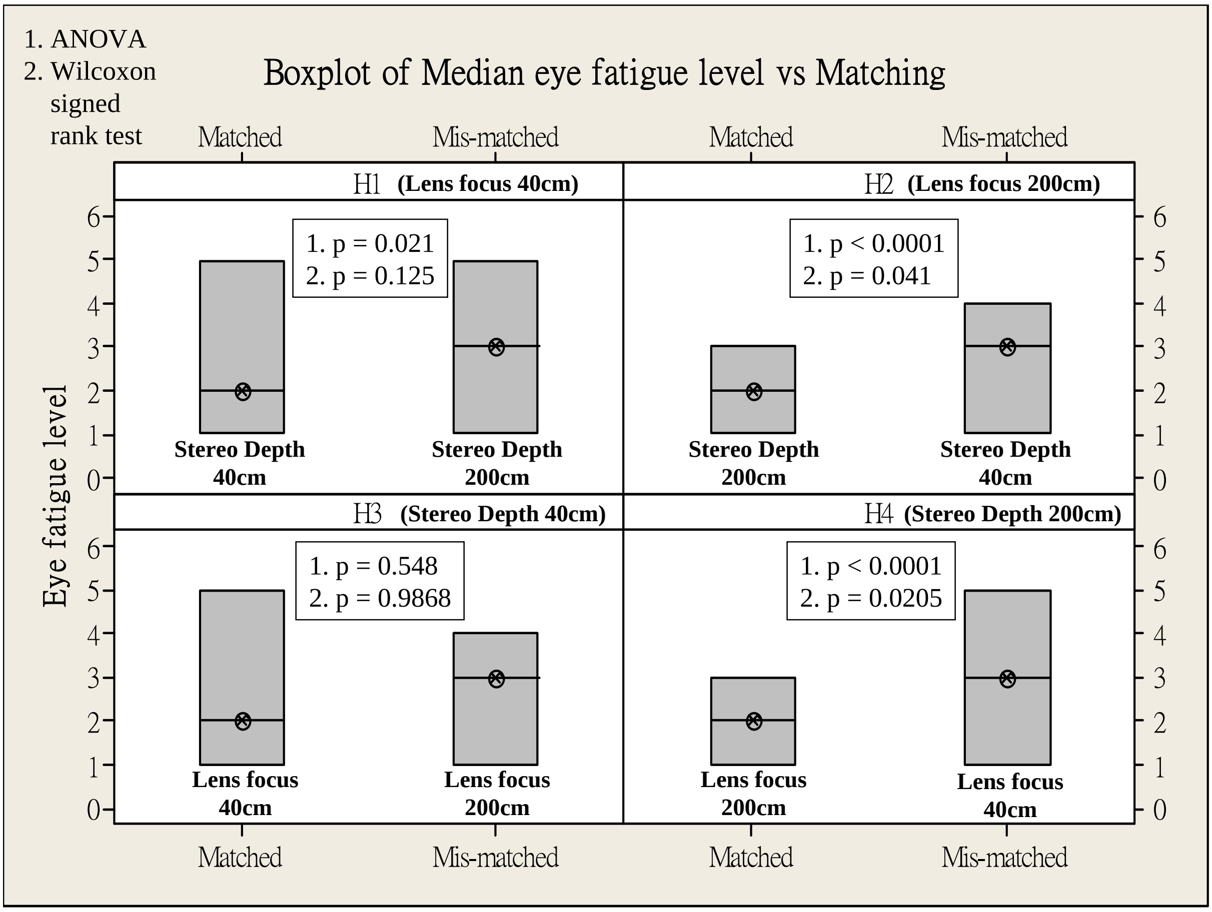

Figure 3.1 Comparisons of median (n=12, with inter-quartile ranges) rated levels of eye fatigue when lens focus equal and not equal to stereo depths of the viewed images. The comparisons are done when lens focus or stereo depth is controlled at 40cm or 200cm corresponding to the testing of hypotheses H1- H4. (NB: p-values in point 1 are the p-values obtained form ANOVAs and p-values in point 2 are the p-values obtained from Wilcoxon signed-rank tests).

Inspections of the comparisons according to hypotheses H1 to H4 in Figure 3.1 indicate a pattern of confounding effects between matching and lens focus and matching and stereo depth.

For the testing of hypothesis H1, when lens focus is controlled at 40 cm, participants viewed images with stereo depths of 40cm ± 0.3D (matched condition) and 200cm ± 0.3D (mis-matched condition). Results of ANOVA indicate that viewing images with matched stereo depth of 40 cm ± 0.3D result in significantly lower levels of eye fatigue than viewing images with mis-matched stereo depth of 200 cm ± 0.3D (p<0.05, $F_{1,383} = 5.38$, ANOVA). However, results of Wilcoxon indicates no significant different (p>0.1, Wilcoxon). Because the data is not normally distributed, the author concludes that the effect of matching is not significant or at most marginally significant. The lack of significant effects is consistent with the result of studies conducted by Emoto et al. (2005) in which no significant difference between the use of fixed focus of 30cm and the use of dynamically matching lens focus is reported, when viewing stereoscopic images with stereo depth cues varying within the range of relative vergence. In this case, there is no confounding effect of lens focus because lens focus has been controlled to 40cm. However, the effect of matching is confounded with stereo depth. A review of optometry literature indicates that converging to images with stereo depth of 40cm will require higher tensions in ocular muscles than converging to images with stereo depth of 200cm (Tyrrell. & Leibowitz. 1990, Jaschinski-Kruza. 1991, Sheedy. 2007), however, isolated effects of convergence on eye fatigue could not be found as effects of convergence often co-found with effects of accommodation. If we hypothesize that more convergence will cause more eye stress, then for the testing of hypothesis H1, the confounding effects of convergence will be in opposite to the effects of matching because more convergence is required in the matched condition. Consequently, the marginal significant reduction of rated levels of eye fatigue in the matched condition (both lens focus and stereo depth are about 40cm) as compared to the mis-matched condition (lens focus = 40cm and stereo depth = 200cm) indicate that the effects of matching on eye fatigue has been neutralized by the opposing confounding effects of stereo depth.

For the testing of hypothesis H2, when lens focus is controlled at 200 cm, participants viewed images with stereo depths of 200cm ± 0.3D (matched condition) and 40cm ± 0.3D (mis-matched condition). Results of both ANOVA and Wilcoxon indicate that viewing images with matched stereo depth of 200 cm ± 0.3D result in significantly lower levels of eye fatigue than viewing images with mis-matched stereo depth of 200 cm ± 0.3D ($p<0.0001$, $F_{1,383} = 32.99$, ANOVA; $p<0.05$, Wilcoxon). In this case, there is no confounding effect of lens focus because lens focus has been controlled to 200cm. However, the effect of matching is confounded with stereo depth. As explained in the last section, if we hypothesize that more convergence will cause more eye stress, then for the testing of hypothesis H2, the confounding effects of convergence will enhance the effects of matching because less convergence is required in the matched condition. Consequently, the significant reduction of rated levels of eye fatigue in the matched condition (both lens focus and stereo depth are about 200cm) as compared to the mis-matched condition (lens focus = 200cm and stereo depth = 40cm) indicate that the effects of matching with enhancing confounding effect of stereo depth will result in significant influence on eye fatigue.

For the testing of hypothesis H3, when stereo depths of all images are controlled at 40cm ± 0.3D, participants viewed these images under lens focus of 40cm (matched condition) and 200cm (mis-matched condition). Results of both ANOVA and Wilcoxon indicate that viewing images under lens focus of 40 cm result in no significant change on eye fatigue than viewing images under lens focus of 200 cm ($p>0.5$, $F_{1,383} = 0.36$, ANOVA; $p>0.5$, Wilcoxon). In this case, there is no confounding effect of stereo depth because it has been controlled to 40cm ± 0.3D. However, the effect of matching is confounded with lens focus. A review of optometry literature indicates that viewing near objects will require higher tensions in ocular muscles than viewing distant images. However, isolated effects of convergence on eye fatigue could not be found as effects of convergence often confound with effects of accommodation (Lie. & Watten. 1994, Sheedy. 2007). If we hypothesize that near accommodation will cause more eye stress, then for the testing of hypothesis H3, the confounding effects of accommodation will be in opposite to the effects of matching because near accommodation is required in the matched condition. Consequently, the lack of significant changes in rated levels of eye fatigue collected in the matched condition (both lens focus and stereo depth are about 40cm) as compared to the mis-matched condition (lens focus = 200cm and stereo depth = 40cm) indicate that the effects of matching on eye fatigue has been neutralized by the opposing confounding effects of accommodation.

For the testing of hypothesis H4, when stereo depth is controlled at 200 cm ± 0.3D, participants viewed images under lens focus of 200cm (matched condition) and 40cm (mis-matched condition). Results of both ANOVA and Wilcoxon indicate that viewing images with matched lens focus of 200 cm result in significantly lower levels of eye fatigue than viewing images with mis-matched lens focus of 40 cm (p<0.0001, $F_{1,383}$ = 55.46, ANOVA; p<0.05, Wilcoxon). In this case, there is no confounding effect of stereo depth because it has been controlled to 200cm ± 0.3D. However, the effect of matching is confounded with lens focus. As explained beforehand, if we hypothesize that near accommodation will cause more eye stress, then for the testing of hypothesis H4, the confounding effects of lens focus will enhance the effects of matching because far accommodation is required in the matched condition. Consequently, the significant reduction of rated levels of eye fatigue in the matched condition (both lens focus and stereo depth are about 200cm) as compared to the mis-matched condition (lens focus = 40cm and stereo depth are about 200cm) indicate that the effects of matching with enhancing confounding effect of stereo depth will result in significant influence on eye fatigue. Table 3.1 summarizes the relationships between the effects of matching and the confounding effects of lens focus and stereo depth in the testing of hypotheses H1 to H4.

Table 3.1 A summary of the relationships between the effects of matching and the confounding effects of lens focus and stereo depth in the testing of hypotheses H1 to H4.

Hypothesis	Controlled factor	Factors compared or tested	Confounding Factor
H1	Lens focus 40cm	Matched (Stereo Depth 40cm ± 0.3D) **VS** Mismatched (Stereo Depth 200cm ± 0.3D)	Stereo Depth (opposite)
H2	Lens focus 200cm	Matched (Stereo Depth 200cm ± 0.3D) **VS** Mismatched (Stereo Depth 40cm ± 0.3D)	Stereo Depth (enhancing)
H3	Stereo Depth 40cm ± 0.3D	Matched (Lens focus 40cm) **VS** Mismatched (Lens focus 200cm)	Lens focus (opposite)
H4	Stereo Depth 200cm ± 0.3D	Matched (Lens focus 200cm) **VS** Mismatched (Lens focus 40cm)	Lens focus (enhancing)

3.2 Survival analysis using Cox Regression

Since the results of ANOVAs indicate that both lens focus, stereo depth, and their two-way interactions all have significant main effects on rated levels of eye fatigue, this section uses Cox Regression to explore the use of lens focus (accommodation response), stereo depth (vergence response), and their interaction (matching effects) as co-variates in survival time analyses.

3.2.1 A brief introduction to survival analyses

Cox regression, which implements the proportional hazards model or duration model, is designed for analysis of time until an event to occur or time between events. In this study, the times taken for eye fatigue level to reach 4 (6 is the maximum rating before a participant will terminate the task and rated level 4 is mild to moderate tiredness related to the subject's eyes) are analyzed.

One or more predictor variables, called covariates, are used to predict a status (event) variable. In this study, the predictor variables were lens focus, stereo depth and their two-way interaction (i.e. matching). The classic univariate example is time from diagnosis with a terminal illness until the event of death (hence survival analysis). The central statistical output is the hazard ratio. (Garson GD, 2008)

The rate of failure at time t (death, or any other event of interest, e.g. eye fatigue level reached to '4') is called the hazard function. The hazard h(t) is modeled as:

$$h(t) = h_0(t) * \exp(b_1X_1 + b_2X_2 + b_3X_3 + \ldots + b_kX_k)$$

where $X_1 \ldots X_k$ are a collection of predictor variables and $h_0(t)$ is the baseline hazard at time t, representing the hazard for a person with the value 0 for all the predictor variables. The constants b_1, b_2, to b_k are regression coefficients.

By dividing both sides of the above equation by $h_0(t)$ and taking logarithms, we obtain:

$$\ln(h(t) / h_0(t)) = b_1X_1 + b_2X_2 + b_3X_3 + \ldots + b_kX_k$$

We call $h(t) / h_0(t)$ the hazard ratio. The coefficients $b_1 \ldots b_k$ are estimated by Cox regression.

The covariate (risk factor, e.g. lens focus) is coded '1' if present and as '0' if absent. Then the quantity $\exp(b_i)$ can be interpreted as the instantaneous relative risk of an event, at any time, for an individual with the risk factor present compared with an individual with the risk factor absent, given both individuals are the same on all other covariates. In this case, the event was eye fatigue level reached '4'.

The cumulative hazard rate through time t: H(t) can be found from:

$H(t) = -\ln(S(t))$

Where S(t) is the cumulative proportion surviving through time t.

h(t) for every t can be calculated from H(t) by:

$h(1) = H(1)$

$h(t) = H(t) – h(t-1)$ for $t >= 2$.

For a cox regression with one predictor variable:

$h(t) = [h_0(t)]\, e^{(bX)}$

When X = 0, $h(t) = [h_0(t)]$, since $e^0 = 1$

When X = 1, $h(t) = [h_0(t)]\, e^{(b)}$

b = Cox regression coefficient, determined by maximum likelihood estimation.

Dividing both sides of the cox regression equation by $h_0(t)$

$$\frac{h(t)}{h_0(t)} = \frac{h_0(t)e^{(bX)}}{h_0(t)}$$

$$\frac{h(t)}{h_0(t)} = e^{(bX)}$$

where exp(b) is the hazard ratio.

This ratio indicates the expected change in the risk of the terminal event when X changes from 0 to 1. (i.e. 1 = presence of the characteristic X)

When X = 0, the hazard ratio = 1.0

When X = 1, the hazard ratio = $e^{(bX)}$ = exp(b)

If the hazard ratio = 1, then the independent variable does not effect survival.

If the hazard ratio is < 1, then the independent variable is associated with increased survival.

If the hazard ratio is > 1, then the independent variable is associated with decreased survival.

3.2.2 Survival analysis: Cox regression on the times taken for eye fatigue level to reach eye fatigue rating level 4

The time taken to reach 4 on the eye fatigue level was defined as the survival time. Survival analysis was performed using Cox regression with lens focus (X), stereo depth (Y) and their two-way interaction XY (i.e. matching) as predictor variables. The predictor variables were binary coded as follows:

X = 0, if lens focus = 200 cm

X = 1, if lens focus = 40 cm

Y = 0, if stereo depth = 200 cm ± 0.3D

Y = 1, if stereo depth = 40 cm ± 0.3D

The definitions of the two predictor variables are summarized in Table 3.2.

Table 3.2 Definitions of the two predictor variables: X and Y in the Cox regression model.

conditions	Lens focus	Stereo depth	X	Y
C1	40 cm	40 cm	1	1
C2	200 cm	200 cm	0	0
C3	40 cm	200 cm	1	0
C4	200 cm	40 cm	0	1

The regression equation is:

$$h(t) = h_0(t) * \exp(b_1X + b_2Y + b_3XY) \quad (3.1)$$

The resulting outputs are the hazard ratios for lens focus, stereo depth and their interaction respectively (i.e. $\exp(b_1)$, $\exp(b_2)$ and $\exp(b_3)$ respectively).

The outputs of Cox regression are shown in table 3.3. It was found that the lens focus is a significant factor ($p = 0.0189$). Although, the interaction factor is marginally significant ($p = 0.0712$), we cannot exclude its existence because of the confounding effect in the experimental design. Substituting suitable binary values (0 or 1) into equation (3.1) and using hazard ratios in Table 3.3, we can calculate the relative hazard $h(t)/h_0(t)$ for each condition. Table 3.4 presents the relative hazard for each condition.

Table 3.3 Results of Cox regression using time taken to reach eye fatigue level 4 as survival time. (N.B. Interaction is the two-way interaction between lens focus and stereo depth)

Dependent Variable	Survival Time (i.e. Time to reach the eye fatigue level of 4)
Censoring Variable	Eye fatigue level
Censoring Value(s)	1 2 3
Ties Handling	BRESLOW

Summary of the Number of Event and Censored Values

Total	Event	Censored	Percent Censored
48	36	12	25.00

Convergence criterion (GCONV=1E-8) satisfied.

Model Fit Statistics

Criterion	Without Covariates	With Covariates
-2 LOG L	245.885	239.701
AIC	245.885	245.701
SBC	245.885	250.451

Testing Global Null Hypothesis: BETA=0

Test	Chi-Square	DF	Pr > ChiSq
Likelihood Ratio	6.1847	3	0.1030
Score	5.9467	3	0.1142
Wald	5.5217	3	0.1373

Analysis of Maximum Likelihood Estimates

Variable	DF	Parameter Estimate	Standard Error	Chi-Square	Pr > ChiSq	Hazard Ratio	95% Hazard Confidence	Ratio Limits
Lens Focus	1	1.20265	0.51241	5.5087	0.0189	3.329	1.219	9.088
Stereo Depth	1	0.81918	0.51862	2.4949	0.1142	2.269	0.821	6.269
Interaction	1	-1.24405	0.68942	3.2562	0.0712	0.288	0.075	1.113

Table 3.4 Relative hazard of the four experimental conditions.

conditions	Lens focus	Stereo depth	Relative hazard
C1	40 cm	40 cm	2.175
C2	200 cm	200 cm	1
C3	40 cm	200 cm	3.329
C4	200 cm	40 cm	2.269

From Table 3.4, by comparing conditions C2 and C4, we can deduce that when lens focus is set at 200 cm, a participant viewing stereoscopic images with mismatched stereo depth of 40cm ± 0.3D would be 2.269 times more likely to reach 4 on the eye fatigue level, when compared with matched stereo depth of 200cm ± 0.3D. This indicates significant benefit of matching lens focus with dynamically changing stereo depth cues when lens focus is set at 200cm.

When lens focus is set at 40 cm, a participant viewing stereoscopic images with mismatched stereo depth of 200cm ± 0.3D would be 3.329/2.175 = 1.53 times more likely to reach 4 on the eye fatigue level, when compared with matched stereo depth of 40cm ± 0.3D. This means that when lens focus is set at 40 cm, viewing images with matched or mismatched stereo depth makes almost no difference.

When stereo depth is within 40 cm ± 0.3D, a subject viewing stereoscopic images with mismatched lens focus of 200cm would be 2.269/2.175 = 1.04 times more likely to reach 4 on the eye fatigue level, when compared with matched lens focus of 40. Which means that when viewing stereoscopic images with stereo depth varying within 40 cm ± 0.3D, using matched or mismatched lens focus makes almost no difference.

When stereo depth is within 200 cm ± 0.3D, a subject viewing stereoscopic images with mismatched lens focus of 40cm would be 3.329 times more likely to reach 4 on the eye fatigue level, when compared with matched lens focus of 200cm. Which means that when viewing stereoscopic images with stereo depth varying within 200 cm ± 0.3D, using matched lens focus has a significant benefit over mismatched lens focus.

The results from survival analysis above further supported the results obtained from the four hypothesis testing reported in section 2.3.3 of chapter 2.

3.3 Linear Regression for the four hypotheses

In survival analyses, time to eye fatigue level 4 has been analyzed. In this section, linear regressions are conducted to analyze the rated eye fatigue levels.

3.3.1 Linear Regression for H1

A regression line was fit using duration and stereo depth as independent variables to predict the average eye fatigue level when lens focus is set at 40 cm. The result is shown in Table 3.5.

Statistic test indicates that the coefficient of duration is significant ($p < 0.0001$) and the coefficient of stereo depth is also significant ($p = 0.0165$). R^2 is 0.9656 indicating a good fit of the regression line.

Table 3.5 Regression of average eye fatigue level against duration (in minutes) and stereo depth (in cm) when lens focus is set at 40cm.

Dependent Variable: Average eye fatigue level

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	88.58725	44.29362	407.28	<.0001
Error	29	3.15385	0.10875		
Corrected Total	31	91.74110			

Root MSE	0.32978	R-Square	0.9656
Dependent Mean	2.90885	Adj R-Sq	0.9633
Coeff Var	11.33704		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	1	-0.01003	0.14157	-0.07	0.9440
Duration	1	0.17975	0.00632	28.43	<.0001
StereoDepth	1	0.00186	0.00072871	2.55	0.0165

The regression equation is:

Average eye fatigue level = -0.01003 + 0.17975*duration + 0.00186*stereo depth

3.3.2 Linear Regression for H2

A regression line was fit using duration and stereo depth as independent variables to predict the average eye fatigue level when lens focus is set at 200 cm. The result is shown in Table 3.6.

The regression equation is:

Average eye fatigue level = 0.68022 + 0.15248*duration - 0.00426*stereo depth

Statistic test indicates that the coefficient of duration is significant ($p < 0.0001$) and the coefficient of stereo depth is also significant ($p < 0.0001$). R^2 is 0.9737 indicating a good fit of the regression line.

Table 3.6 Regression of average eye fatigue level against duration (in minutes) and stereo depth (in cm) when lens focus is set at 200cm.

Dependent Variable: Average eye fatigue level

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	66.96593	33.48296	535.98	<.0001
Error	29	1.81163	0.06247		
Corrected Total	31	68.77756			

Root MSE	0.24994	R-Square	0.9737
Dependent Mean	2.45573	Adj R-Sq	0.9718
Coeff Var	10.17784		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	1	0.68022	0.10729	6.34	<.0001
Duration	1	0.15248	0.00479	31.82	<.0001
StereoDepth	1	-0.00426	0.00055230	-7.72	<.0001

3.3.3 Linear Regression for H3

A regression line was fit using duration and lens focus as independent variables to predict the average eye fatigue level when stereo depth is set at 40 cm. The result is shown in table 3.7.

Table 3.7 Regression of average eye fatigue level against duration (in minutes) and lens focus (in cm) when stereo depth is set at 40cm.

Dependent Variable: Average eye fatigue level

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	80.73502	40.36751	590.71	<.0001
Error	29	1.98177	0.06834		
Corrected Total	31	82.71680			

Root MSE	0.26141	R-Square	0.9760
Dependent Mean	2.77865	Adj R-Sq	0.9744
Coeff Var	9.40795		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	1	0.16720	0.11222	1.49	0.1470
Duration	1	0.17227	0.00501	34.37	<.0001
Lensfocus	1	0.00022786	0.00057765	0.39	0.6961

The regression equation is:

Average eye fatigue level = 0.1672 + 0.17227*duration + 0.00022786*lens focus

Statistic test indicates that the coefficient of duration is significant (p <0.0001). However, the coefficient of lens focus is not significant (p = 0.6961). R^2 is 0.9760 indicating a good fit of the regression line.

3.3.4 Linear Regression for H4

A regression line was fit using duration and lens focus as independent variables to predit the average eye fatigue level when stereo depth is set at 200 cm. The result is shown in Table 3.8.

Table 3.8 Regression of average eye fatigue level against duration (in minutes) and lens focus (in cm) when stereo depth is set at 200cm.

Dependent Variable: Average eye fatigue level

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	76.70426	38.35213	293.57	<.0001
Error	29	3.78857	0.13064		
Corrected Total	31	80.49284			

Root MSE	0.36144	R-Square	0.9529
Dependent Mean	2.58594	Adj R-Sq	0.9497
Coeff Var	13.97722		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	1	0.89361	0.15516	5.76	<.0001
Duration	1	0.15996	0.00693	23.08	<.0001
Lensfocus	1	-0.00589	0.00079868	-7.38	<.0001

The regression equation is:

Average eye fatigue level = 0.89361 + 0.15996*duration - 0.00589*lens focus

Statistic test indicates that the coefficient of duration is significant ($p < 0.0001$) and the coefficient of lens focus is also significant ($p < 0.0001$). R^2 is 0.9497 indicating a good fit of the regression line.

3.4 Confounding effects of apparent stimuli size on eye fatigue

It has been hypothesized in H2 that: at lens focus 200cm, the eye fatigue level at stereo depth 200cm ± 0.3D (a matched condition C2) will be significantly lower than that of at stereo depth 40cm ± 0.3D (a mismatched condition C4). However, the apparent size of Landolt C rings at stereo depth 40cm ± 0.3D are much larger than those at stereo depth 200cm ± 0.3D. Figures 3.2a and 3.2b shows the Landolt C rings at stereo depth 200cm and at stereo depth 40cm respectively. It is possible that participants viewing targets with larger apparent size is more comfortable. Therefore, one could hypothesis that: at lens focus 200cm, the eye fatigue level at stereo depth 40cm ± 0.3D (a mismatched condition C4) will be significantly lower than that of at stereo depth 200cm ± 0.3D (a matched condition C2) because of apparent size effect.

However, it turns out that our original hypothesis of H2 is true. Namely, at lens focus 200cm, the eye fatigue level at stereo depth 200cm ± 0.3D (a matched condition C2) is, indeed, significantly lower than that of at stereo depth 40cm ± 0.3D (a mismatched condition C4). Indicating that, under the viewing condition of stereo depth at 40cm ± 0.3D with lens focus of 200cm can cause much uncomfortable viewing situation despite of its larger apparent stimuli size.

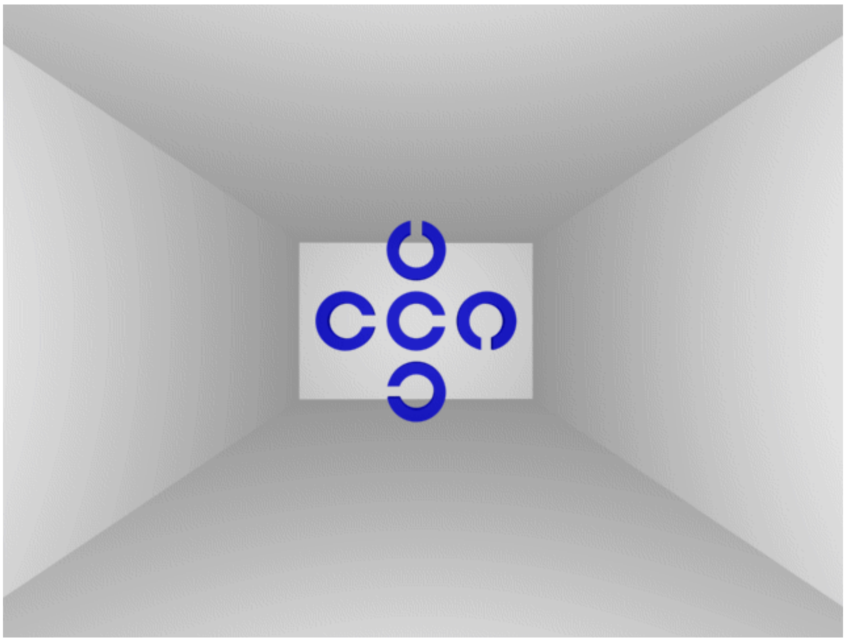

Figure 3.2a The Landolt C rings at stereo depth 200cm.

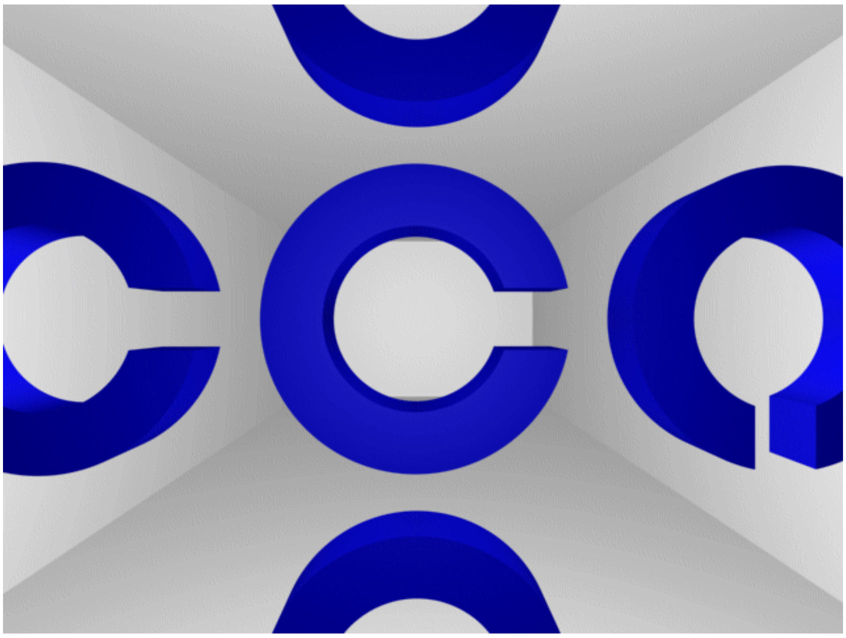

Figure 3.2b The Landolt C rings at stereo depth 40cm.

3.5 Effect of order of presentation of conditions on eye fatigue

In order to verify whether there is any adaptation or learning effect of the subjects over time. Pearson correlation was conducted with presentation order of conditions versus averaged eye fatigue level over 30 minutes (the whole experimental duration). If the coefficient of correlation is significant, then eye fatigue may be positively or negatively related to the order of presentation of conditions. The coefficient of correlation is -0.07923 ($p = 0.5924$). Therefore, the order of presentation of conditions is not correlated with eye fatigue.

3.6 Effect of duration on eye fatigue

Since duration is a significant effect from the result of ANOVA presented in sections 2.3.2 and 2.3.3, this section will investigate this effect in detail.

Figure 3.3 shows the averaged eye fatigue level over time for all the four conditions. From the graph, it can be seen that eye fatigue increases with time in general. The rate of increase is much slower for condition 2 (lens focus 200cm, stereo depth 200cm ± 0.3D), when compare with other four conditions.

Figure 3.4 shows the median eye fatigue level over time for the two conditions: C2 and C4. Where C2 represents a matched condition of lens focus 200cm and stereo depth 200cm ± 0.3D, while C4 represents a mismatched condition of lens focus 200cm and stereo depth 40cm ± 0.3D. The figure indicates that in most of the time, the median of condition C2 is lower than or equal to the 25^{th} percentile line of condition C4 in the whole course of the experiment. Obvious difference is observed at 14 minutes where the 75^{th} percentile data of condition C2 is even lower than the 25^{th} percentile data of condition C4. These findings indicate significant benefit of matching lens focus with stereo depth at 200cm over 30 minutes of exposure time.

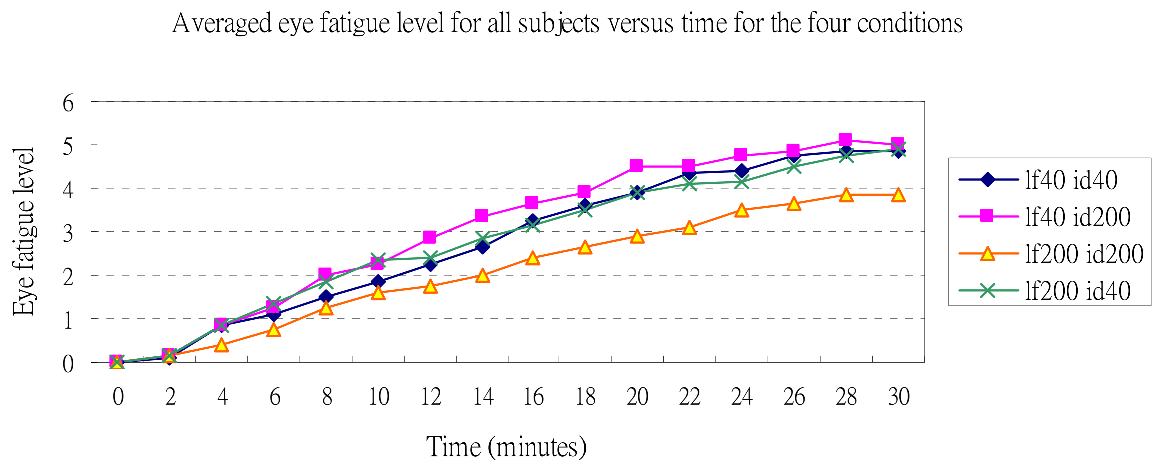

Figure 3.3 A time series plot showing change of averaged eye fatigue level over time for the four conditions. (N.B. lf40 = lens focus 40cm; lf200 = lens focus 200cm; id40 = stereo depth 40cm ± 0.3D; id200 = stereo depth 200cm ± 0.3D)

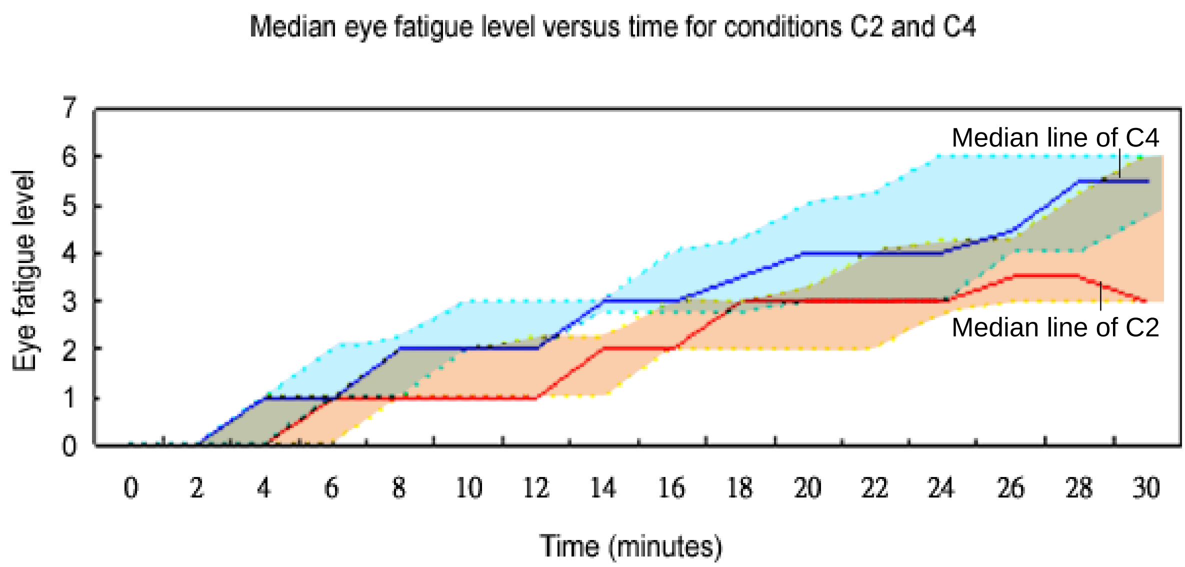

Figure 3.4 A time series plot showing change of median eye fatigue level over time for the two conditions C2 (lens focus = 200cm, stereo depth = 200cm ± 0.3D) and C4 (lens focus = 200cm, stereo depth = 40cm ± 0.3D). (N.B. The upper blue area covers the 25th percentile to 75th percentile data for C4 and the lower red area covers the 25th percentile to 75th percentile data for C2)

Figure 3.5 shows the median eye fatigue level over time for the two conditions: C2 and C3. Where C2 represents a matched condition of lens focus 200cm and stereo depth 200cm ± 0.3D, while C3 represents a mismatched condition of lens focus 40cm and stereo depth 200cm ± 0.3D. The figure indicates that in most of the time, the median of condition C2 is always lower than the 25th percentile line of condition C3 in the whole course of the experiment. Obvious differences are observed at 14 minutes and 20 minutes where the 75th percentile data of condition C2 is even lower than the 25th percentile data of condition C3. These findings indicate significant adverse effect of using mismatched lens focus of 40cm to view images with stereo depth of 200cm ± 0.3D over 30 minutes of exposure time.

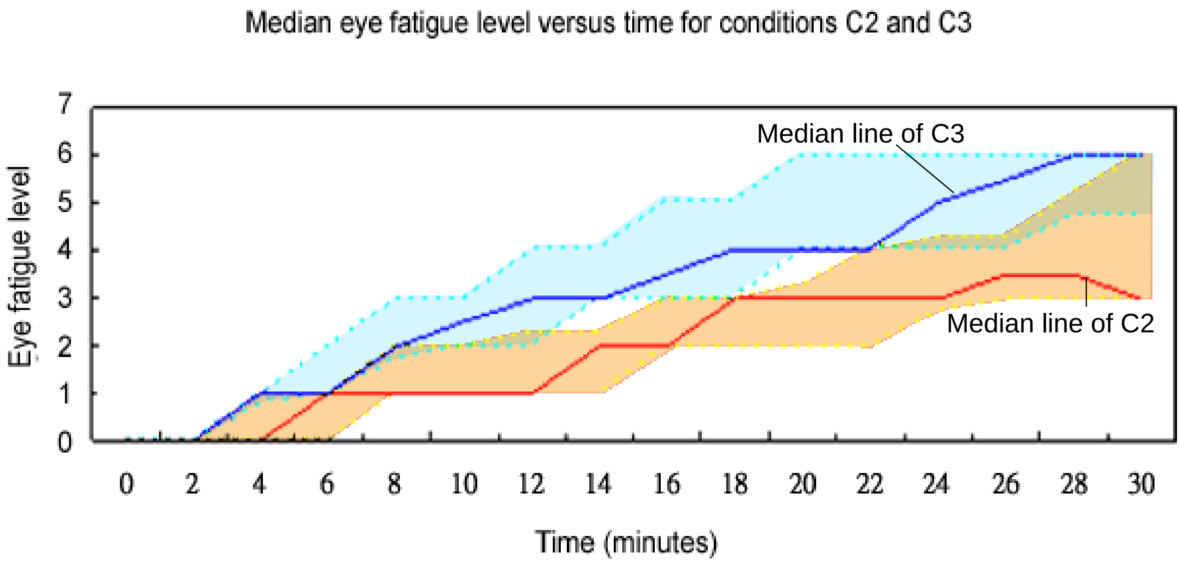

Figure 3.5 A time series plot showing change of median eye fatigue level over time for the two conditions C2 (lens focus = 200cm, stereo depth = 200cm ± 0.3D) and C3 (lens focus = 40cm, stereo depth = 200cm ± 0.3D). (N.B. The upper blue area covers the 25th percentile to 75th percentile data for C3 and the lower red area covers the 25th percentile to 75th percentile data for C2)

3.7 Reliability and suitability of using 7-point eye fatigue ratings

In this study, a 7-point eye fatigue ratings was used to evaluate eye fatigue of the subjects. This raised a problem on the reliability and suitability of using this rating scale. Different units of eye fatigue ratings have been used in previous studies: Yano et al. (2004) and Emoto et al. (2005) have used a 5 point scale, Kuze and Ukai (2008) have used a 7 point scale, Mon-Williams and Wann (1998) have used a 10 point scale. Since, there is no standard method to quantify eye fatigue, a 7 point scale is used with its definition based on a 7 point nausea ratings used in previous studies (Golding & Kerguelen. 1992, So, Lo & Ho. 2001) with modification to make it suitable for this study. Although, 7 point nausea ratings is used to study motion sickness, modification of its definition for studying eye fatigue is suitable because levels of eye fatigue are compatible with levels of motion sickness.

3.8 Effect of amplitude of accommodation on eye fatigue

Inspection of change of eye fatigue level versus time for some subjects revealed some interesting phenomena. Take subject S6 (see figure 3.6) as an example, it seems like the eye fatigue level didn’t increase too much with time under all condition. One hypothesis for this result is that the subject may have a larger amplitude of accommodation, so he can be more tolerant than other subjects when viewing at a near distance for a long time. Since amplitude of accommodation decreases with age, the eye fatigue level for an elder subject (e.g. S10) should increase more quickly than other younger subjects. However, this is not the case in this study (see figure 3.7 and compare with other subjects’ data in Appendix A). Therefore, it would also be possible that the amplitude of accommodation of S10 may not be too small.

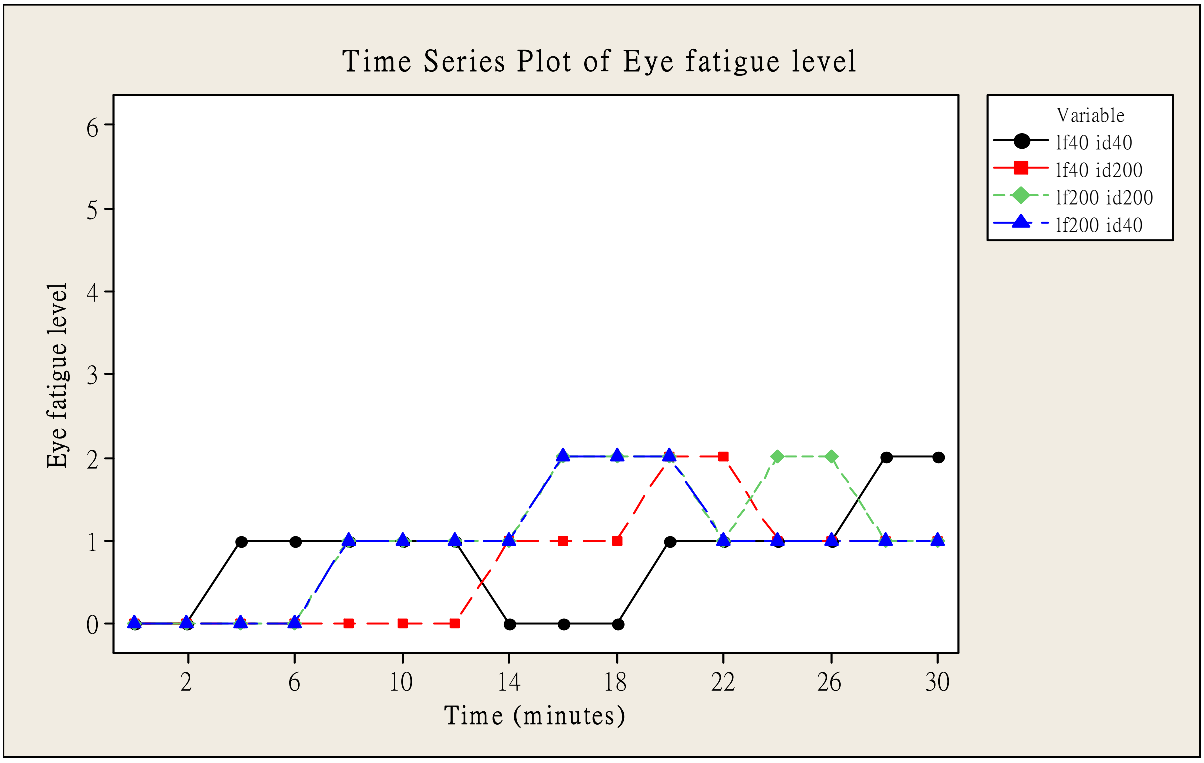

Figure 3.6 Change of eye fatigue level over time for S6.

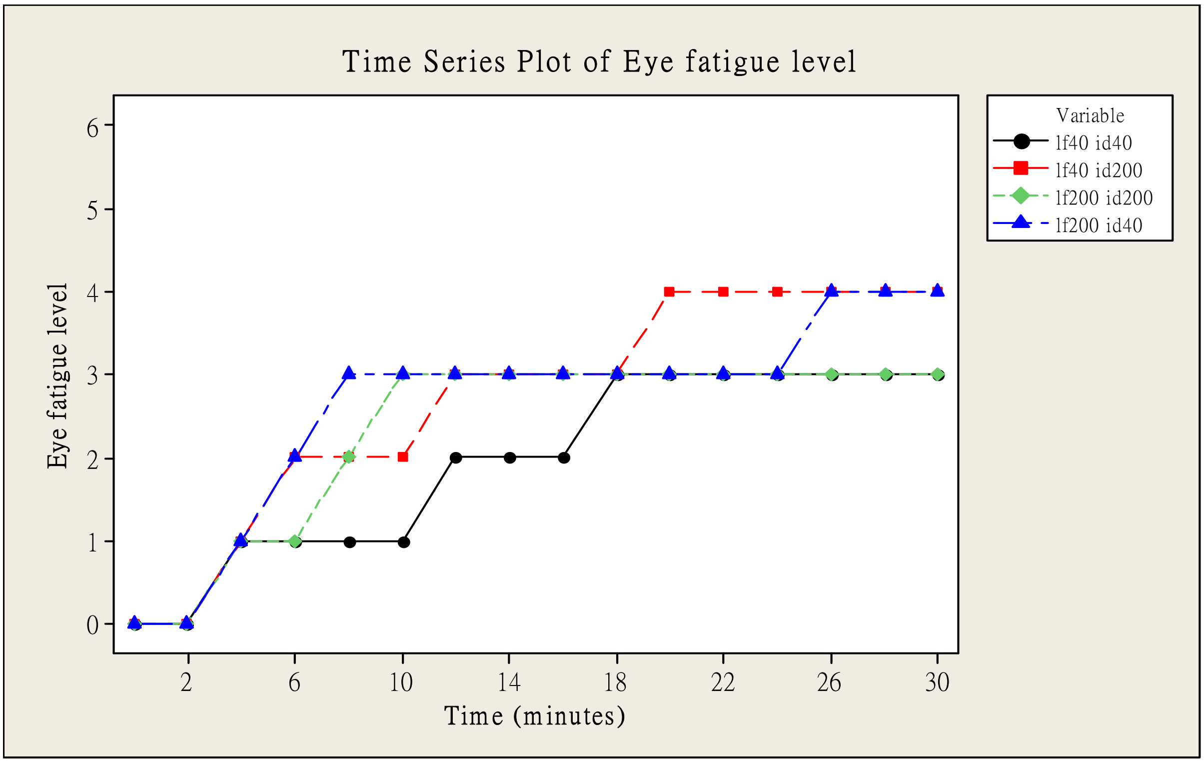

Figure 3.7 Change of eye fatigue level over time for S10.

Table 3.9 shows the amplitude of accommodation measured from some subjects including S6 and S10, under environmental luminance of 200 lux. Subjects S4 and S9 have left the university and quitted the study by the time the measurement was taken. Therefore, their data was not available. In measuring the amplitude of accommodation, a push-up to blur method was used. In which, a distance-corrected subject held a finely printed journal paper (i.e. manuscript of So, Lo & Ho, 2001) with font size of 11 in Times New Roman style and brought it closer to the eyes until the fine print just begin to blur. The distance was recorded and the whole procedure was repeated 5 times. The results were averaged and reciprocal was taken to obtain the amplitude of accommodation. From the table, one can see that, the amplitude of accommodation decreases with age. S10 has the lowest amplitude among all subjects and S6 has near the same amplitude as other young subjects with age of around 25. It seems like the change of eye fatigue level against time is not related to the amplitude of accommodation. There should be some other factors which deserve further investigation.

Table 3.9 Amplitudes of accommodation measured from some subjects with their ages.

Subject	Age	Amplitude of Accommodation (dioptre)
S12	20	17.86
S11	20	14.62
S2	23	13.51
S8	20	12.1
S3	27	10.8
S7	20	10.44
S1	27	8.96
S6	25	8.53
S5	24	7.24
S10	45	2.32

CHAPTER 4

CONCLUSIONS, LIMITATIONS AND FUTURE WORK

4.1 Conclusions

The effects of matching lens focus with dynamically changing stereoscopic depth cues (stereo depth) on the eye fatigue level when viewing a binocular micro-display have been studied at near (40cm) and distant (200cm) accommodation.

When using a head-mounted display (HMD) of fixed lens focus of 200cm, viewing stereo images with changing stereo depths at around 200cm ± 0.3D for 30 minutes will generate significantly less rated levels of eye fatigue than viewing similar images with changing stereo depths around 40cm ± 0.3D for the same time (ANOVA: $p < 0.0001$; Wilcoxon: $p < 0.05$). This finding is important and carries serious implications to those manufacturers of HMDs with fixed lens focus of 200cm (e.g., iMD Ltd.). The current results suggest that game developers who is developing computer games for HMDs with fixed lens focus of 200cm should use stereo images of stereo depths around 200cm± 0.3D instead of 40cm± 0.3D. For this finding, the lens focus is fixed at 200cm (i.e., distant accommodation) and, therefore, the results are not confounded with the effects of accommodation. However, the author acknowledges that the significant increases in eye fatigue when stereo depths are not matched with lens focus are confounded with the effects of changing stereo depths. To isolate the effects of changing stereo depth with the effects of matching lens focus and stereo depth, the study has been repeated using images with stereo depths controlled at 200cm± 0.3D. Data suggest that significant decreases in rated levels of eye fatigue can be generated when the HMDs of matched lens focus (i.e., 200cm) are used instead of mis-matched lens focus (i.e., 40cm) (ANOVA: $p < 0.0001$; Wilcoxon: $p < 0.05$). In this case, the effects of matching lens focus and stereo depth have been isolated from the effects of changing stereo depths but the author acknowledges that the finding is confounded with the effects of accommodation. In summary, viewing stereo images with stereo depths matched within ±0.3D of the lens focus can significantly reduce the rated levels of eye fatigue when the confounding effects of accommodation has been controlled to 200cm or when the effects of confounding effects of convergence has been controlled to viewing images of stereo depths about 200cm. As explained in Chapter 3, the effects of matching lens focus with stereo depth is the two-way interacting effects of lens focus and stereo depth and will be inevitably be confounded with either the effects of lens focus or stereo depth, a further examination of the confounding factors suggests that the effects of matching on eye fatigue are significant when its effects are enhanced by the confounding factors (see Chapter 3).

When the confounding effects of accommodation and convergence are in opposite to the effects of matching lens focus and stereo depth, viewing images with stereo depths mis-matched with lens focus result in similar rated levels of eye fatigue. In particular, data suggest that viewing images with stereo depths of 40cm ± 0.3D with HMDs of fixed lens focus of 40cm and 200cm will result in similar levels of eye fatigue. Also, viewing images with stereo depths of 40cm ± 0.3D and 200cm ± 0.3D with the same HMD of fixed lens focus of 40cm will result in similar levels of eye fatigue. These findings suggest that adjusting the lens focus to match with the changing stereo depths may not be beneficial – a finding that is against our hypotheses H1 and H3 and against the finding of (Shibata *et al*. 2005) reporting the significant benefits of adjusting lens focus. This is not an encouraging result for those who develop new technology to dynamically adjust the lens focus of HMDs (e.g. Sugihara *et al.* 1999, Emoto *et al*. 2005). As explained in Chapter 3, the lack of benefits of adjusting lens focus in these cases are mainly due to the opposing confounding factors of either accommodation or convergence. In summary, the results suggest that adjusting lens focus of a

HMD to match with the stereo depths of the presented stereo images may not be beneficial if the adjustment involve reducing the lens focus from distant (200cm) to near (40cm).

Results of survival analyses indicate that changing lens focus (i.e., changing accommodation) is a significant ($p<0.05$) predicting factor on rated level of eye fatigue and matching interaction effects between lens focus and stereo depth is a marginal significant ($p<0.1$) predicting factor on levels of eye fatigue. Results of survival analyses indicate that with the use of a HMD of fixed lens focus of 200cm, participants viewing images with mis-matched stereo depths of 40cm ± 0.3D are 2.27 times more likely to reach 'mild to moderate eye tiredness' as compared to viewing images with matched stereo depths of 200cm ± 0.3D.

Results from the study conducted by Mon-Williams and Wann (1998) indicate a significant increase in eye fatigue symptoms after viewing a stereoscopic cross sign oscillate between 40cm to infinity at a viewing distance of 40cm for 10 minutes. In effect, Mon-Williams and Wann had created a mismatched condition with lens focus fixed at 40cm. However, from the results reported in section 2.3.3.1, there is only marginal difference in eye fatigue level between match and mismatch conditions when lens focus is set to 40cm. So, the increase in eye fatigue symptoms reported by Mon-Williams and Wann could be attributed to the duration effect. This is because significant duration effect was found for all four conditions in this study.

4.2 Limitations of this study and future work

Limitations in this study and recommendations for future work are discussed in this section.

The experiment was designed to study the effect of matching on eye fatigue level. Since the matching effects are the two-way interaction between the effects of lens focus and the effects of stereo depth, inevitable co-founding will occur and should be acknowledged. However, the four conditions have been analyzed in pair to isolate either the confounding factor of lens focus or stereo depth.

In this study, only 40 cm and 200 cm are chosen as the lens focus and stereo depth cues. This has limited the scope of the conclusion drawn. The conclusion can only be valid on lens focus at 40 cm and 200 cm. Although, linear regression had been performed using lens focus as independent variable. We cannot tell whether the relationship between lens focus and stereo depth is linear or not. Therefore, more levels of lens focus and stereo depth cues should be studied.

Although the stereo depths of images are varied in this study, images of different stereo depths are presented in discrete sequence rather than continuous moving images. This has limited the scope of application of this study. Stereo depth changing in continuous manner could be used in future studies.

The interactions between age and other factors were not meaningful. There should be some other factors which interact with each other and affect the eye fatigue level. Therefore, more participants or subjects could be used to investigate, for example, the effect of gender, visual acuities, etc on the eye fatigue level.

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APPENDIX A

RAW DATA COLLECTED FROM EACH SUBJECT

Key:

lf40 = lens focus at 40cm

lf200 = lens focus at 200cm

id40 = stereo depth cues appropriate to the depths of 40cm ± 0.3 dioptres.

id200 = stereo depth cues appropriate to the depths of 200cm ± 0.3 dioptres.

Subject No. 1 (S1)

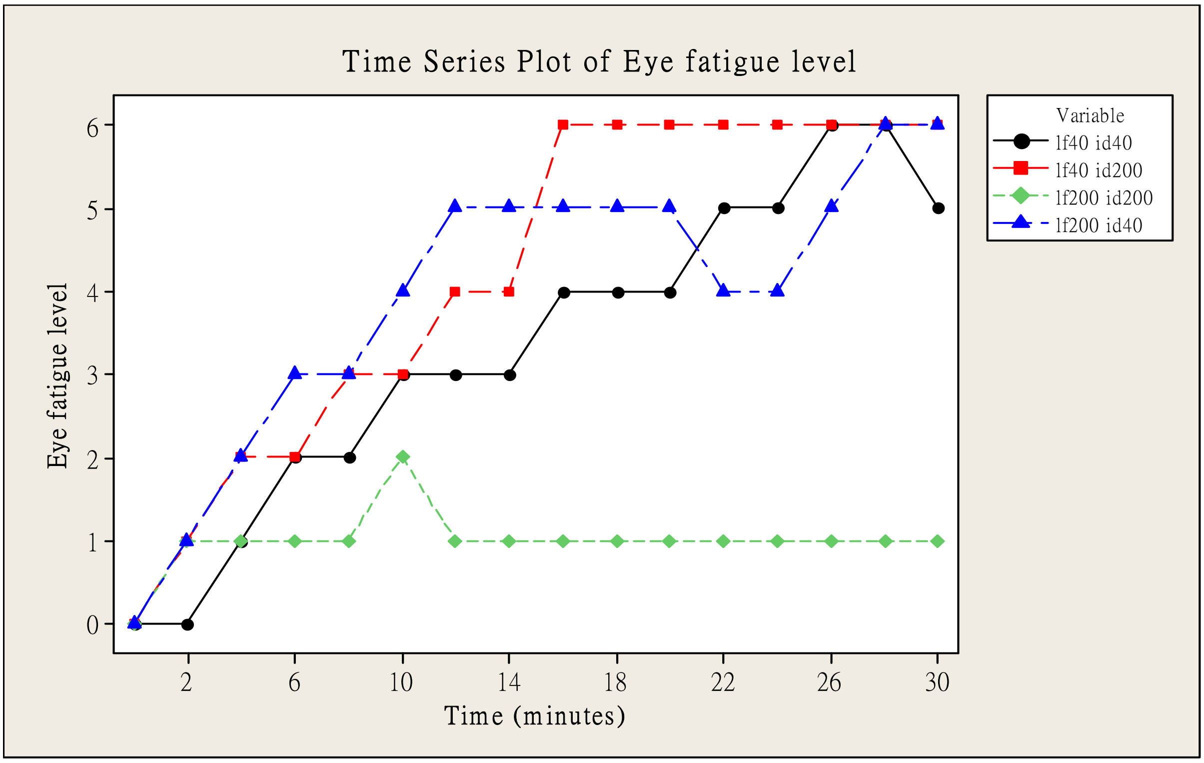

Figure A.1a Change of eye fatigue level over time for S1.

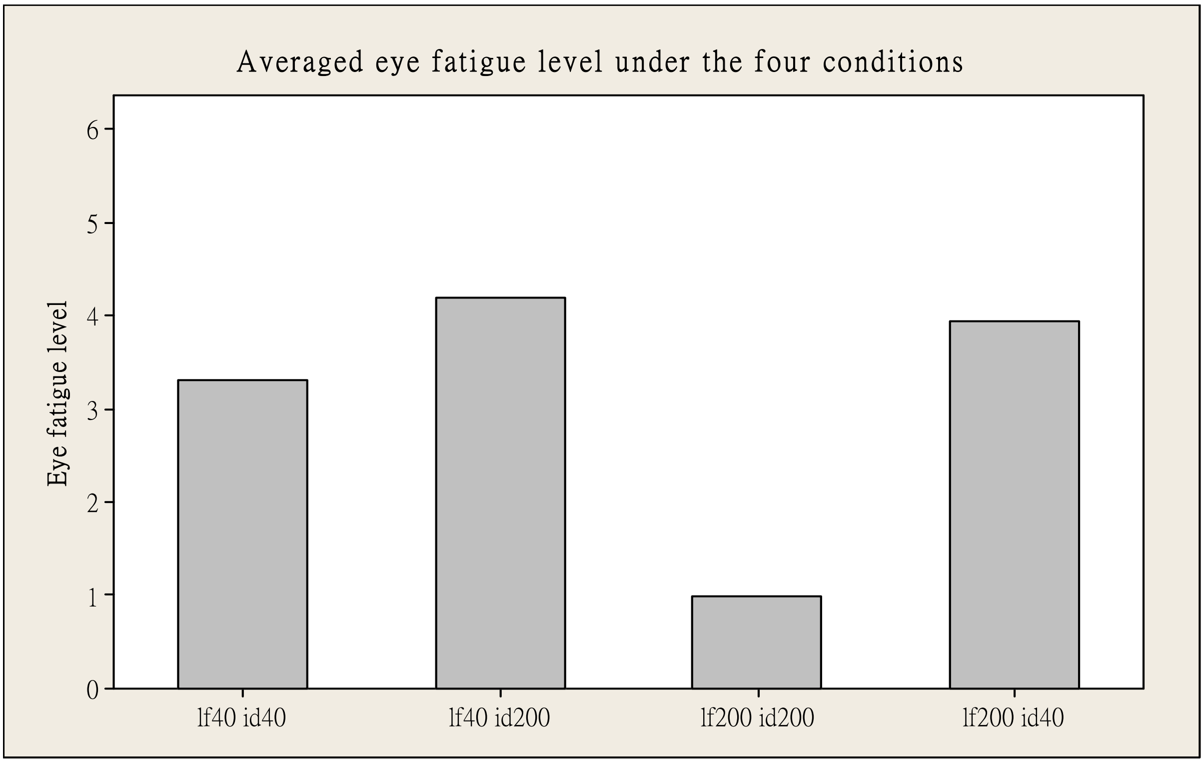

Figure A.1b Averaged eye fatigue level under the four conditions for S1.

Subject No. 2 (S2)

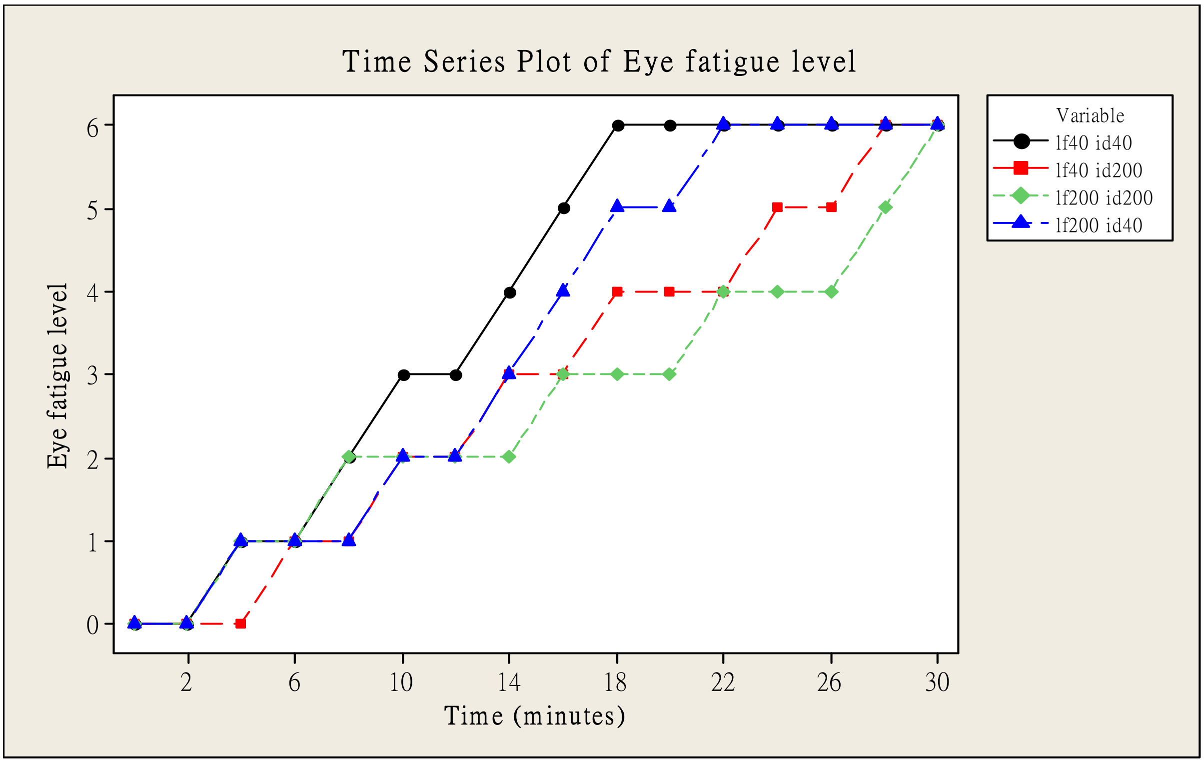

Figure A.2a Change of eye fatigue level over time for S2.

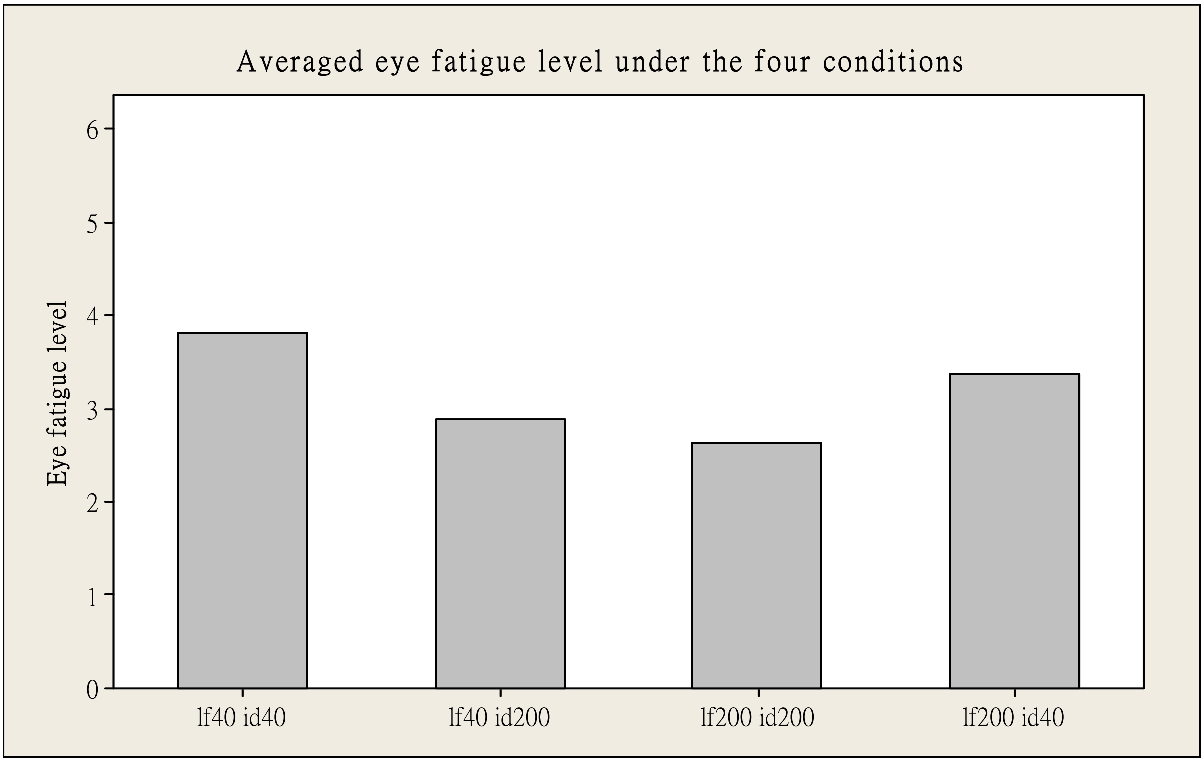

Figure A.2b Averaged eye fatigue level under the four conditions for S2.

Subject No. 3 (S3)

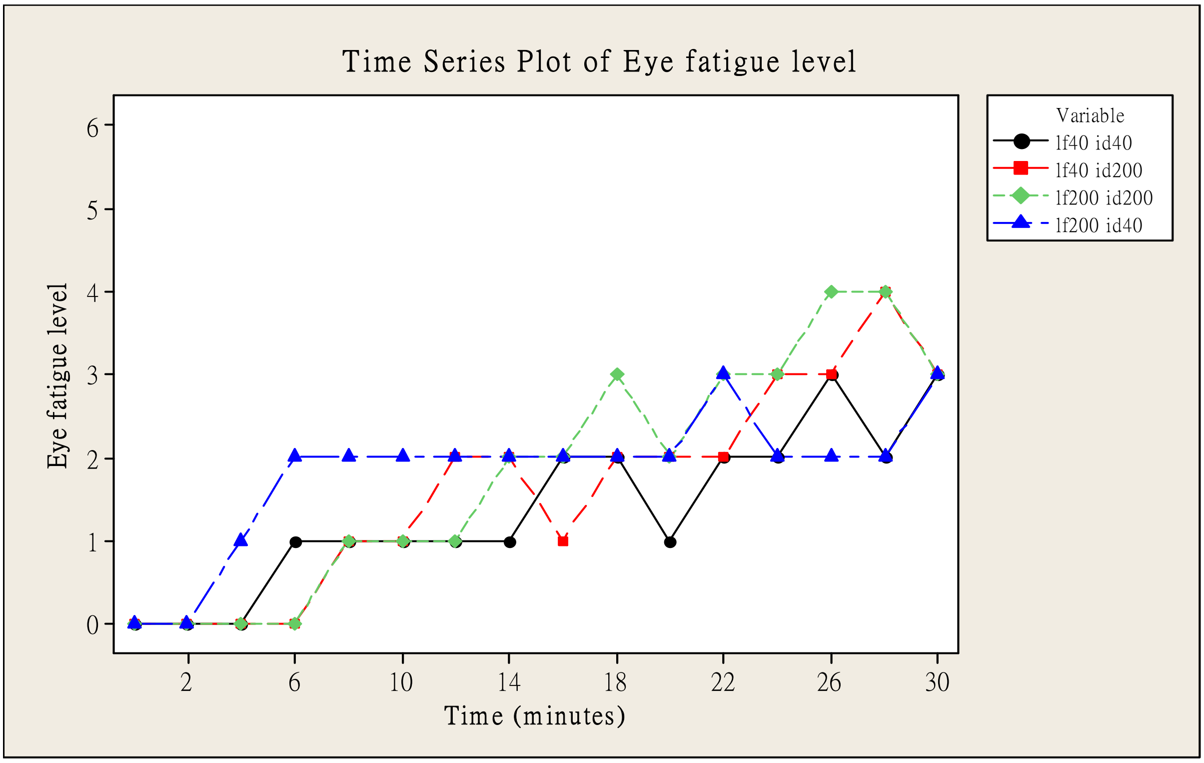

Figure A.3a Change of eye fatigue level over time for S3.

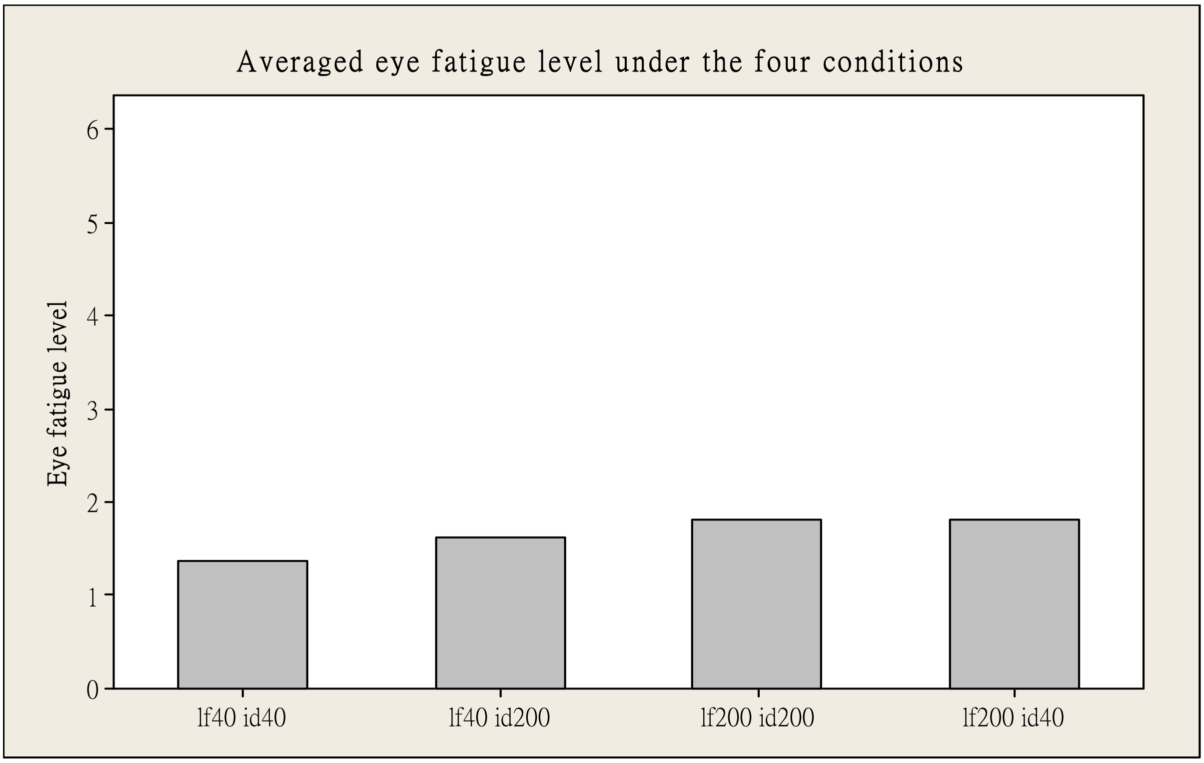

Figure A.3b Averaged eye fatigue level under the four conditions for S3.

Subject No. 4 (S4)

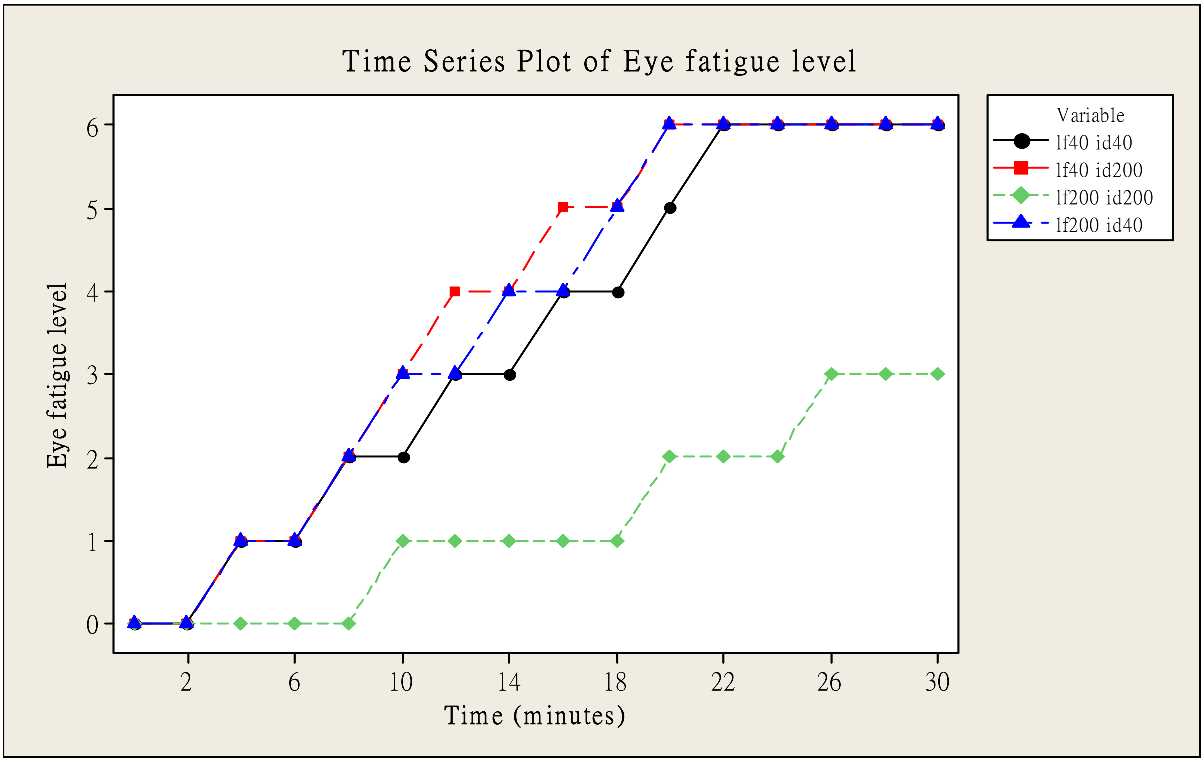

Figure A.4a Change of eye fatigue level over time for S4.

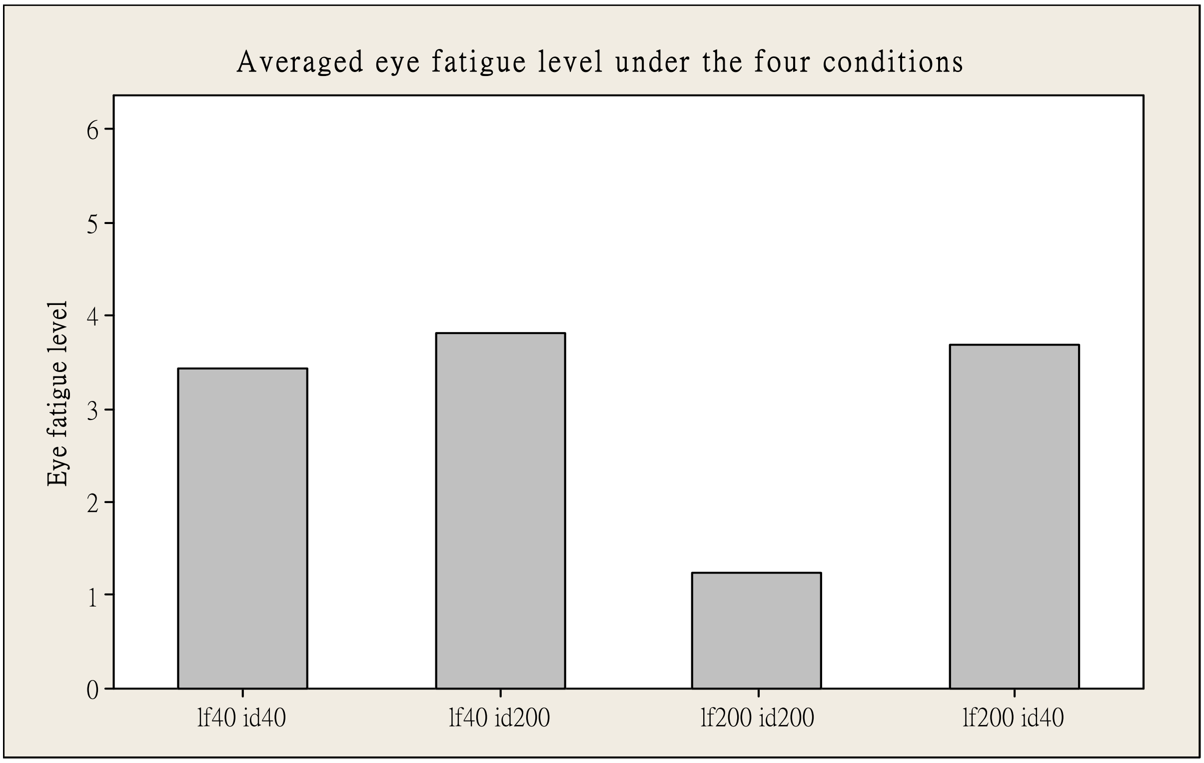

Figure A.4b Averaged eye fatigue level under the four conditions for S4.

Subject No. 5 (S5)

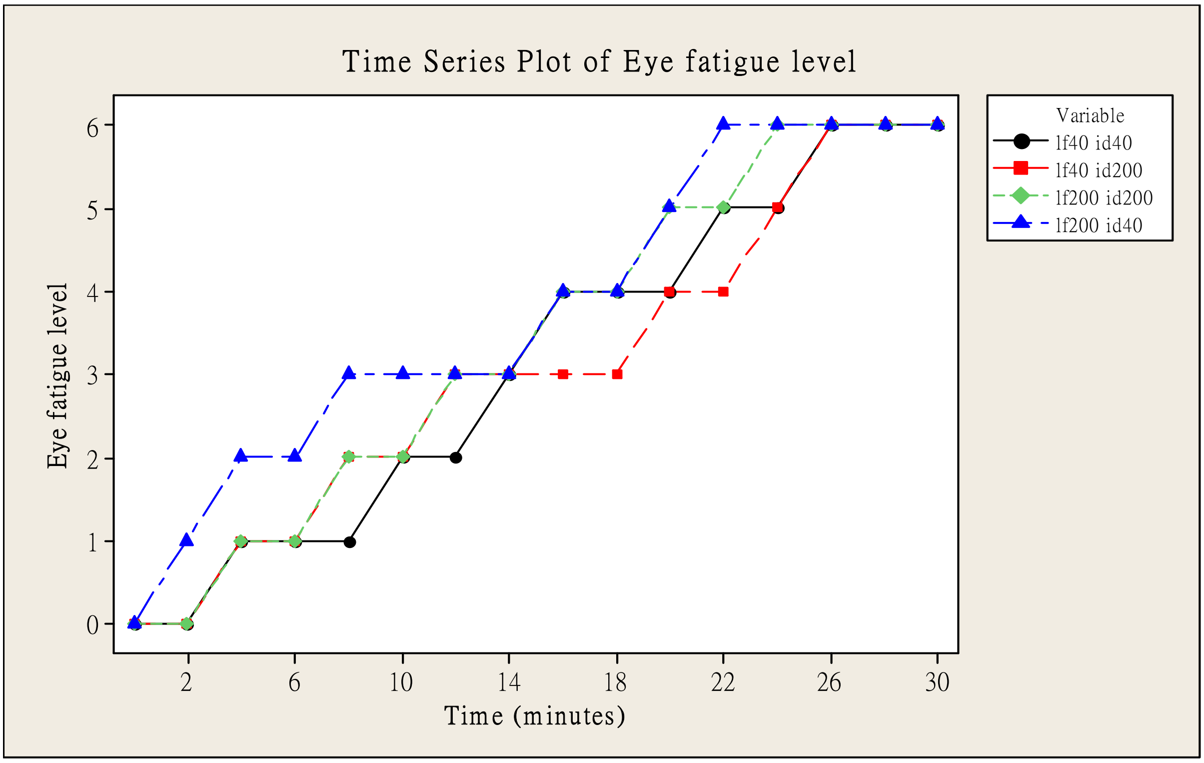

Figure A.5a Change of eye fatigue level over time for S5.

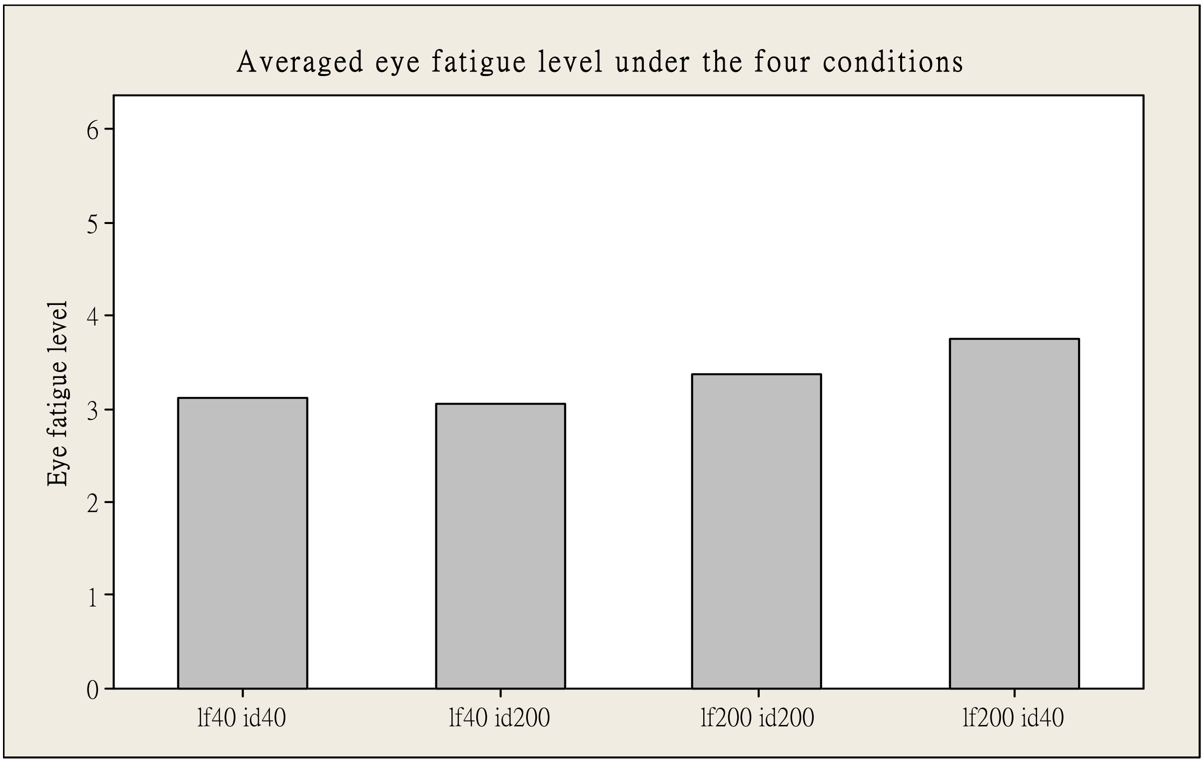

Figure A.5b Averaged eye fatigue level under the four conditions for S5.

Subject No. 6 (S6)

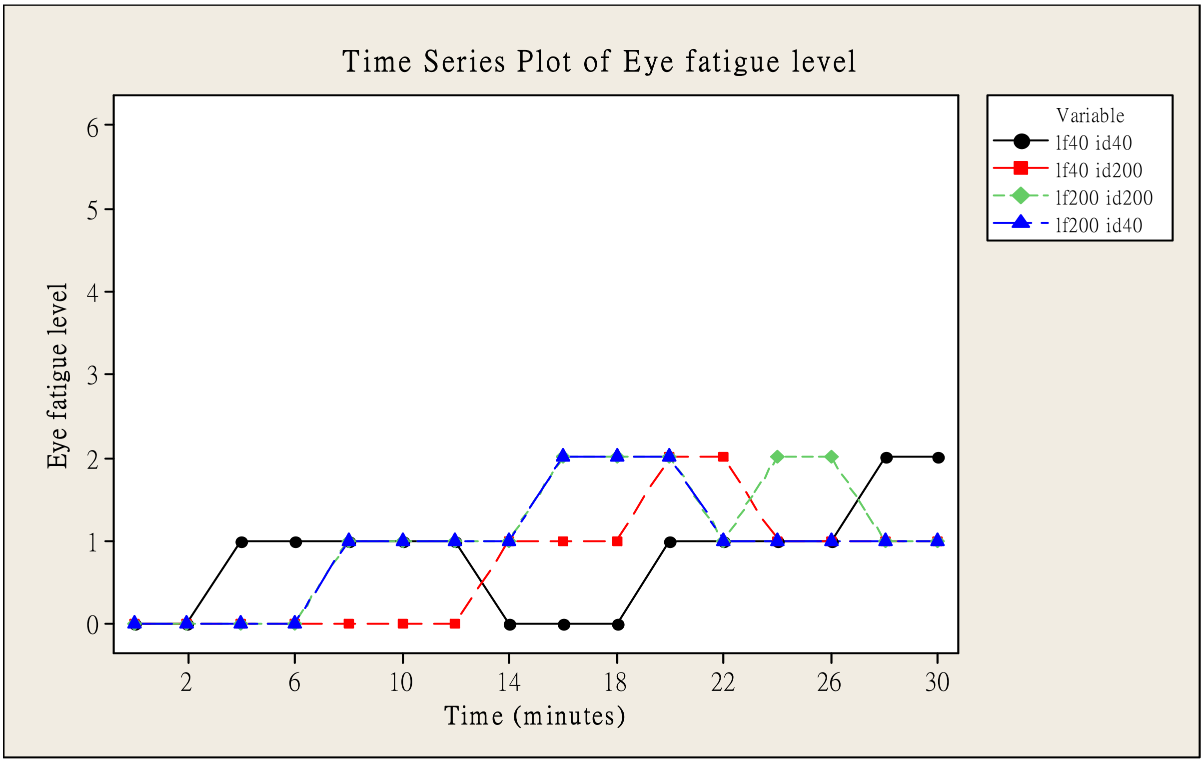

Figure A.6a Change of eye fatigue level over time for S6.

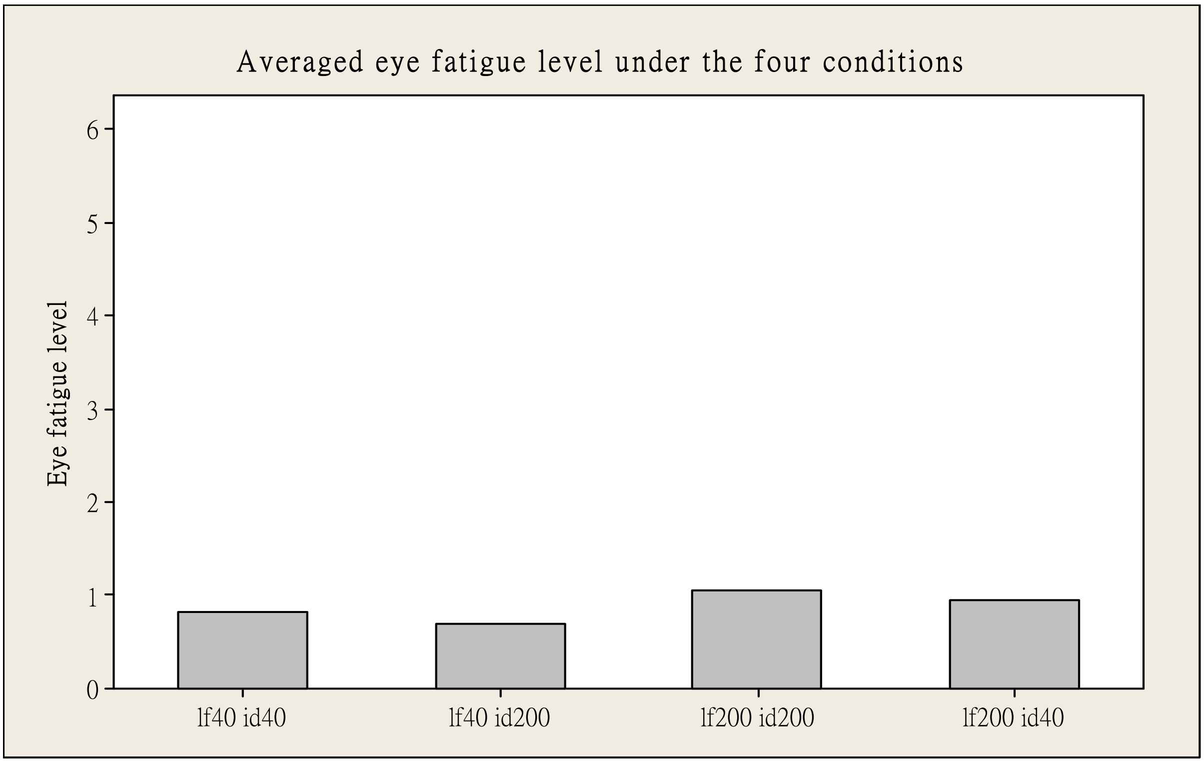

Figure A.6b Averaged eye fatigue level under the four conditions for S6.

Subject No. 7 (S7)

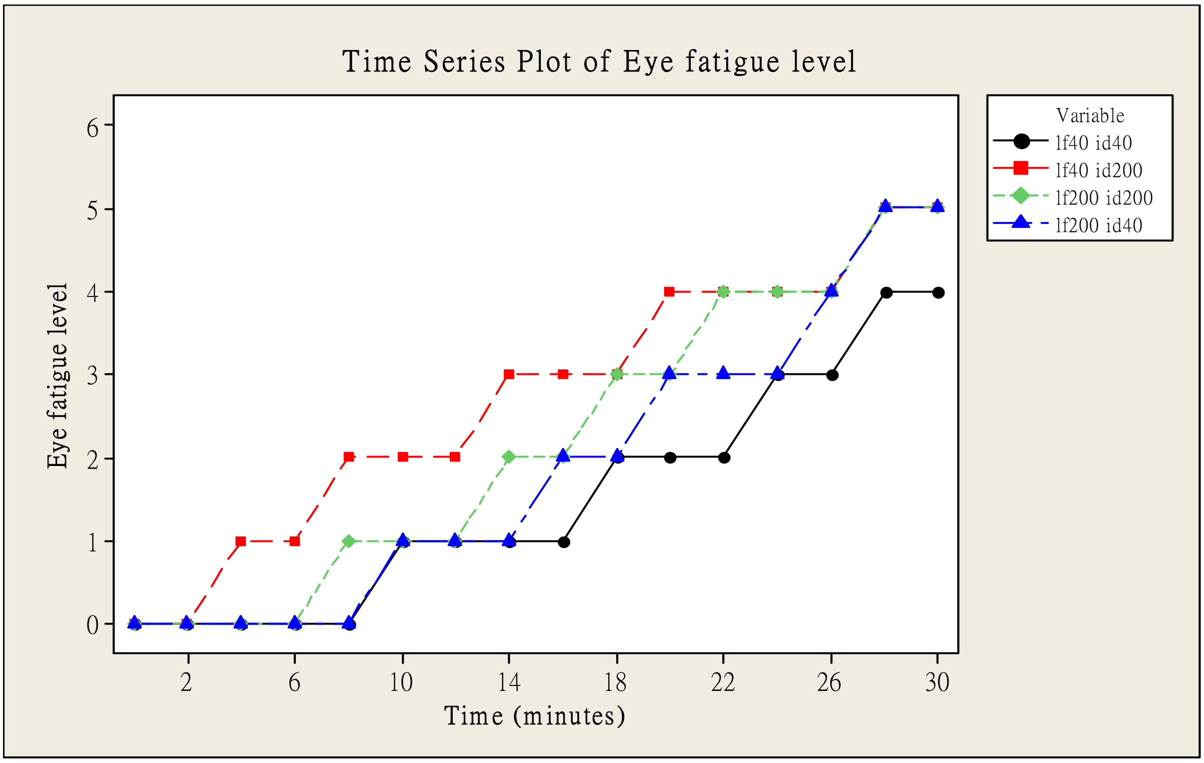

Figure A.7a Change of eye fatigue level over time for S7.

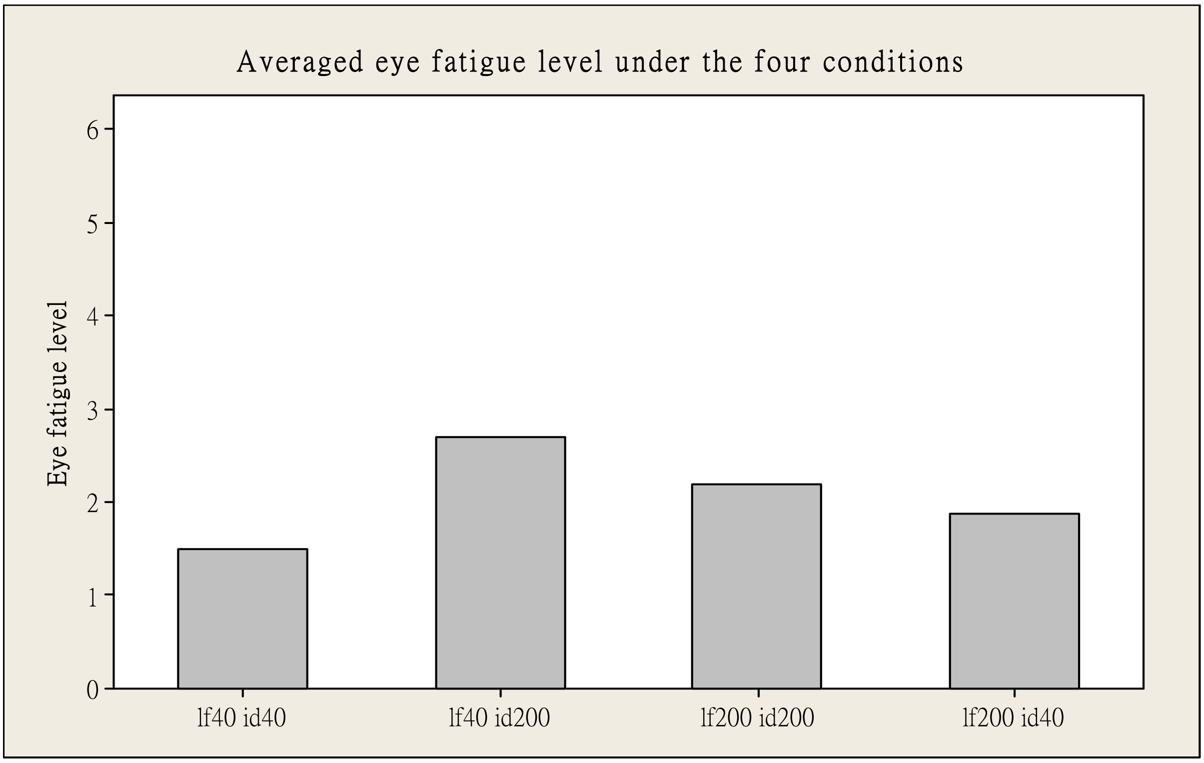

Figure A.7b Averaged eye fatigue level under the four conditions for S7.

Subject No. 8 (S8)

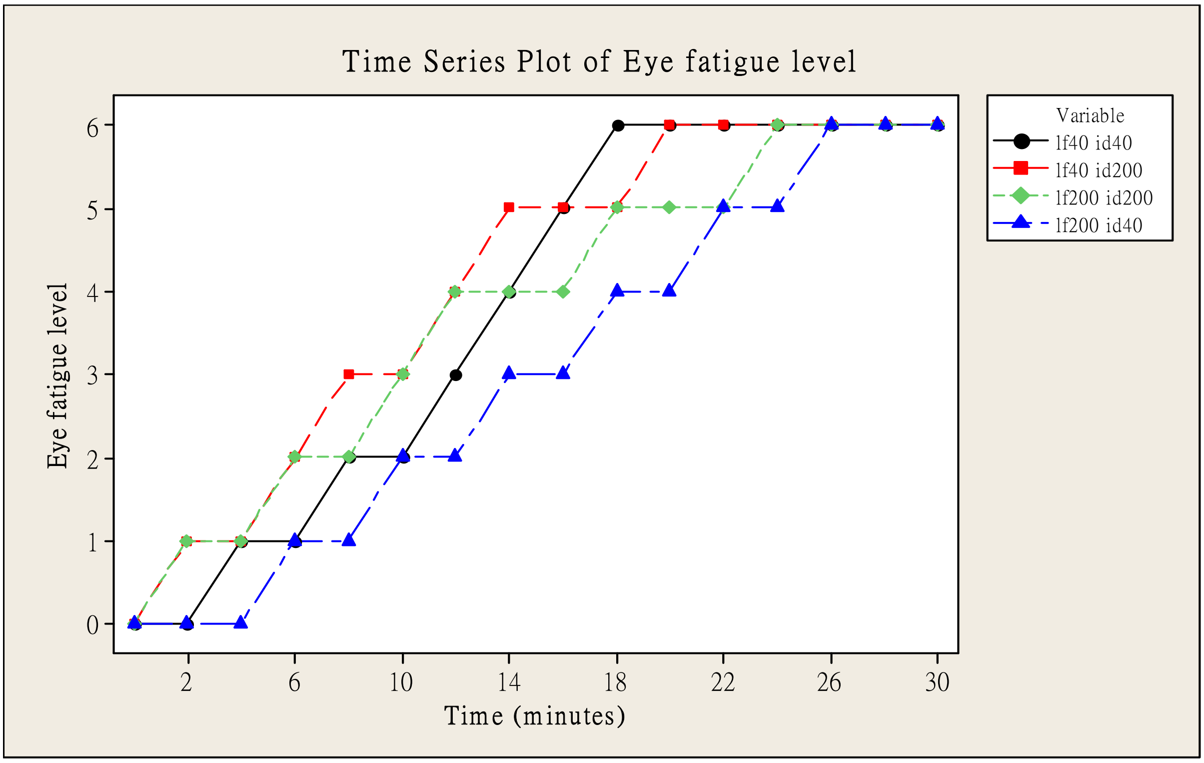

Figure A.8a Change of eye fatigue level over time for S8.

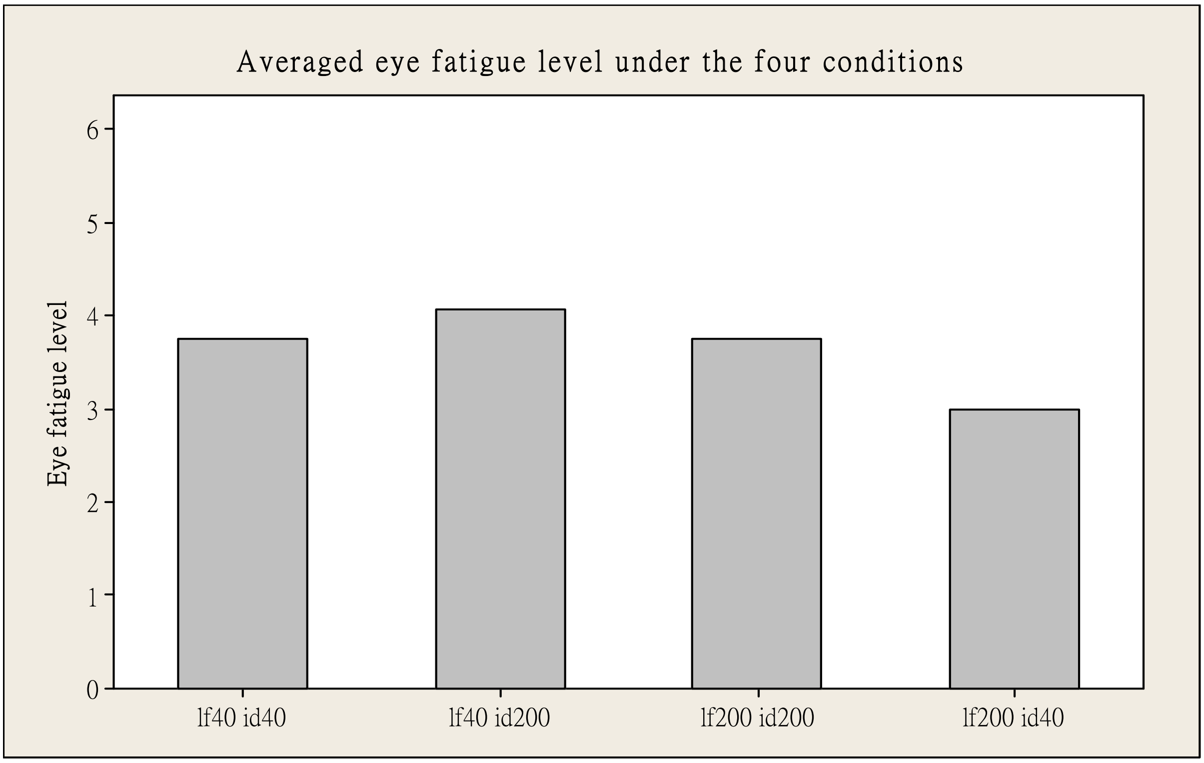

Figure A.8b Averaged eye fatigue level under the four conditions for S8.

Subject No. 9 (S9)

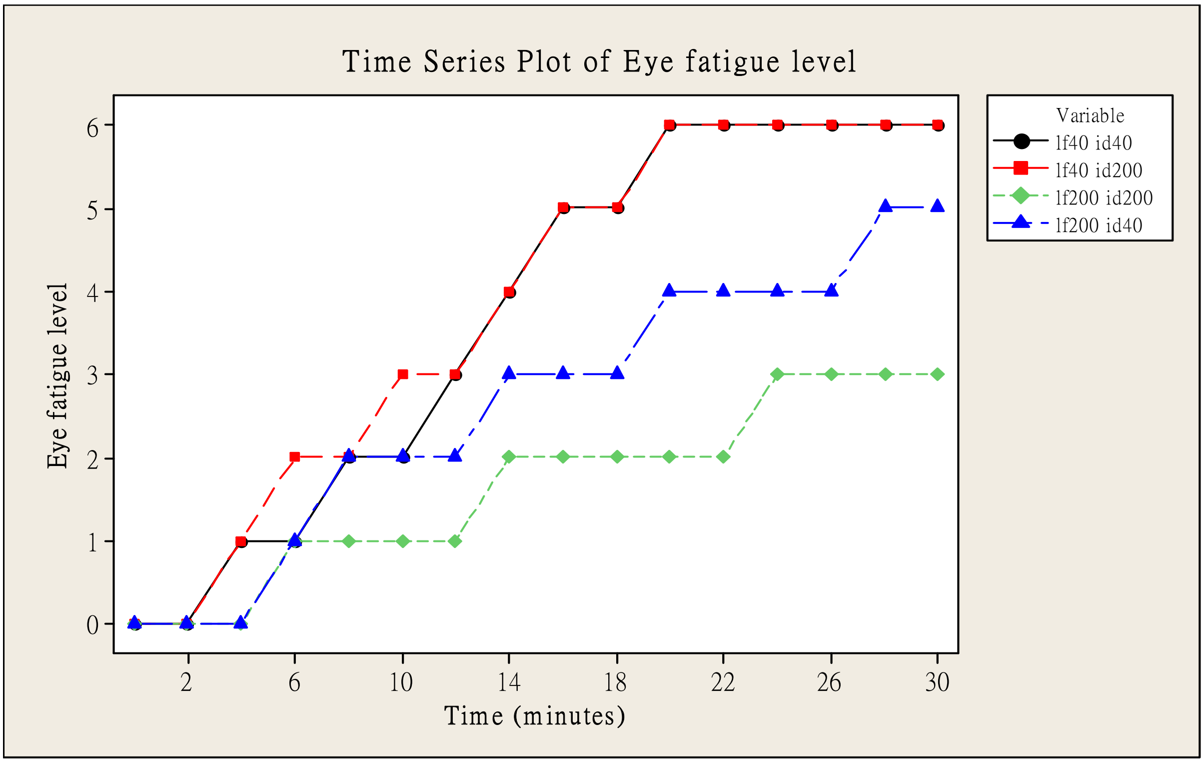

Figure A.9a Change of eye fatigue level over time for S9.

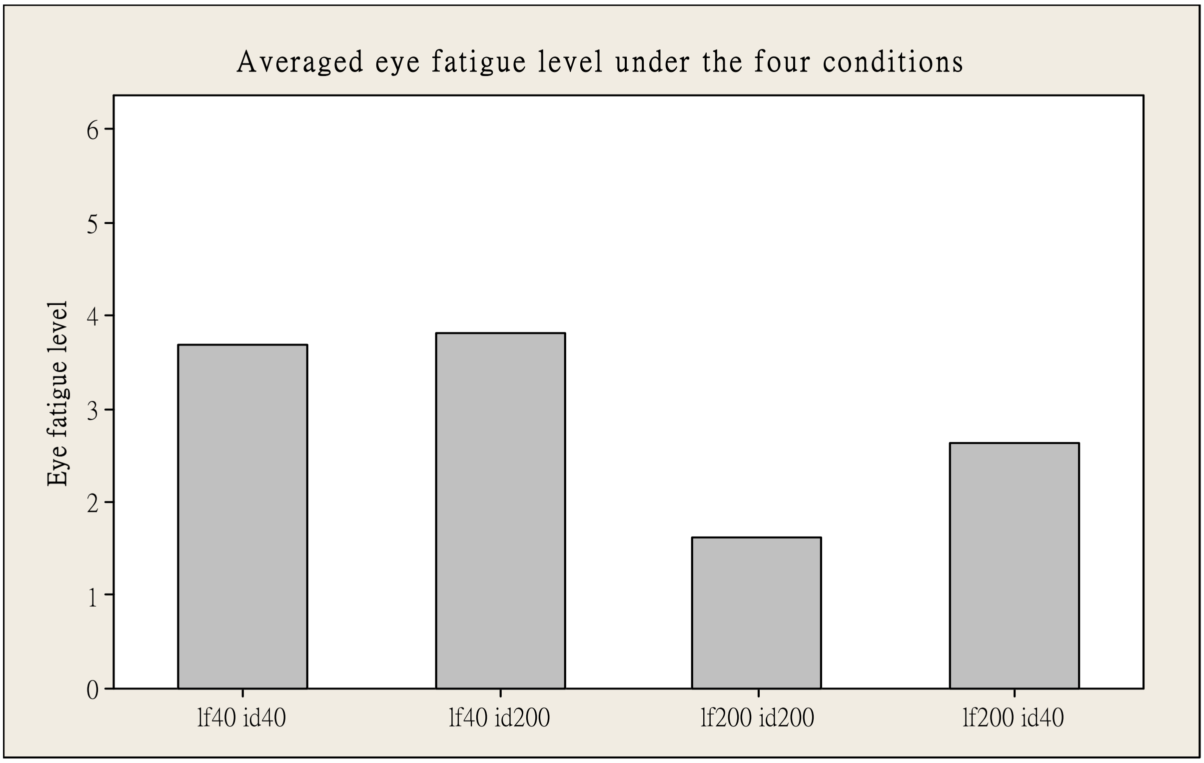

Figure A.9b Averaged eye fatigue level under the four conditions for S9.

Subject No. 10 (S10)

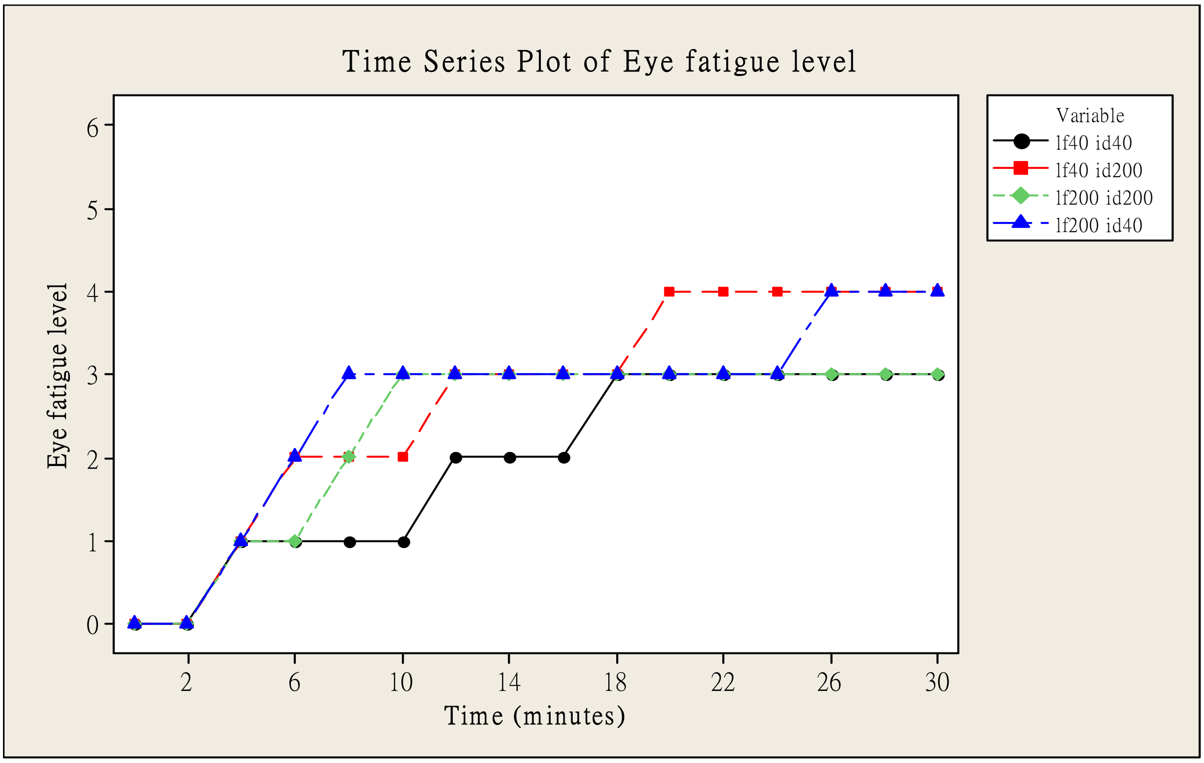

Figure A.10a Change of eye fatigue level over time for S10.

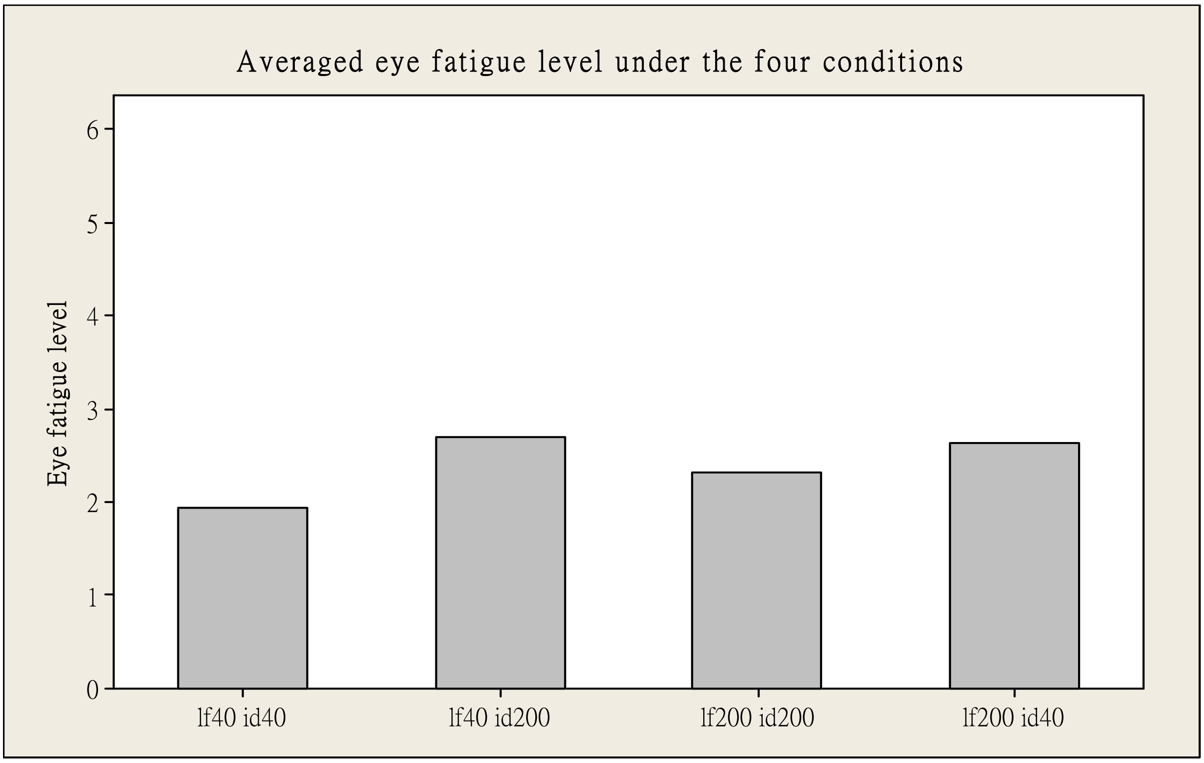

Figure A.10b Averaged eye fatigue level under the four conditions for S10.

Subject No. 11 (S11)

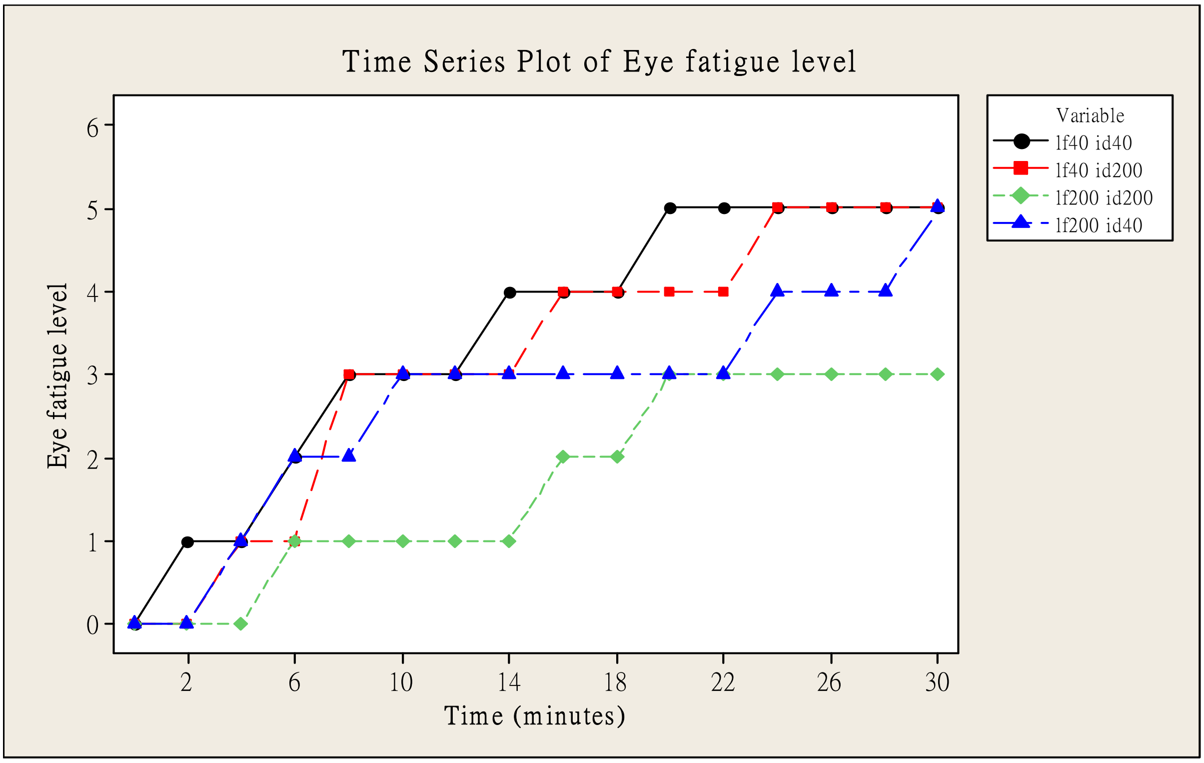

Figure A.11a Change of eye fatigue level over time for S11.

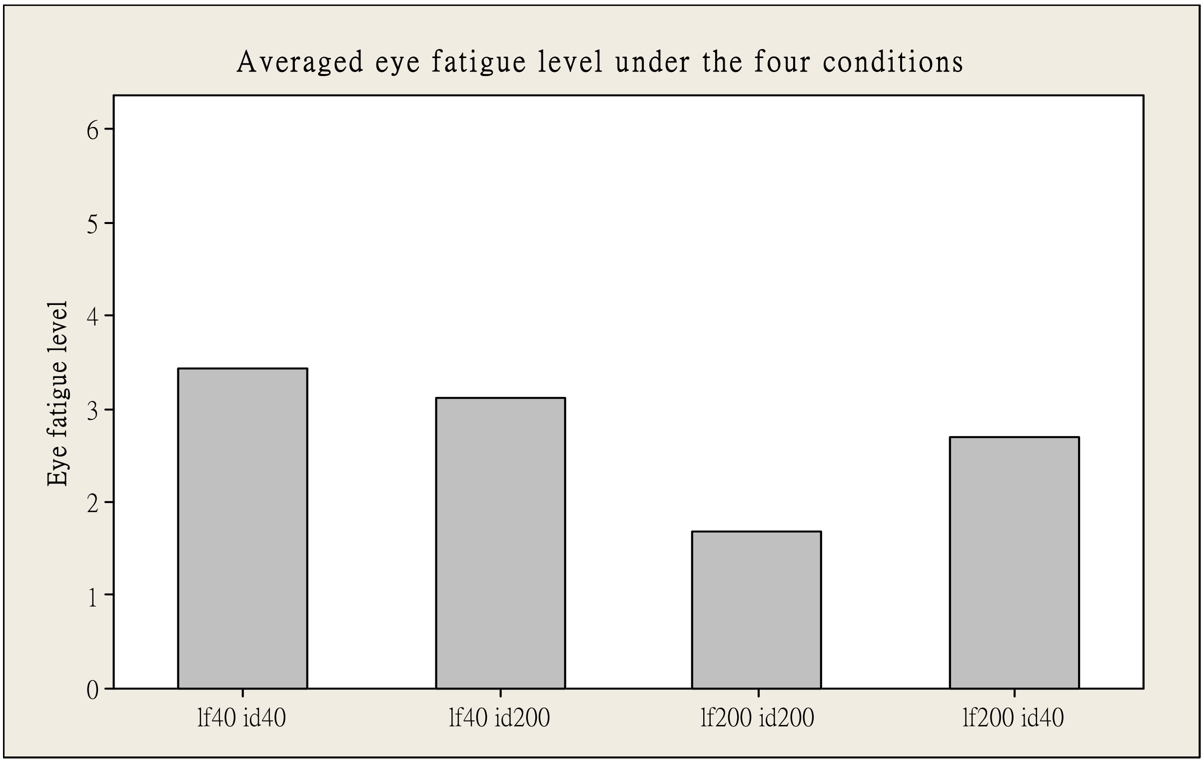

Figure A.11b Averaged eye fatigue level under the four conditions for S11.

Subject No. 12 (S12)

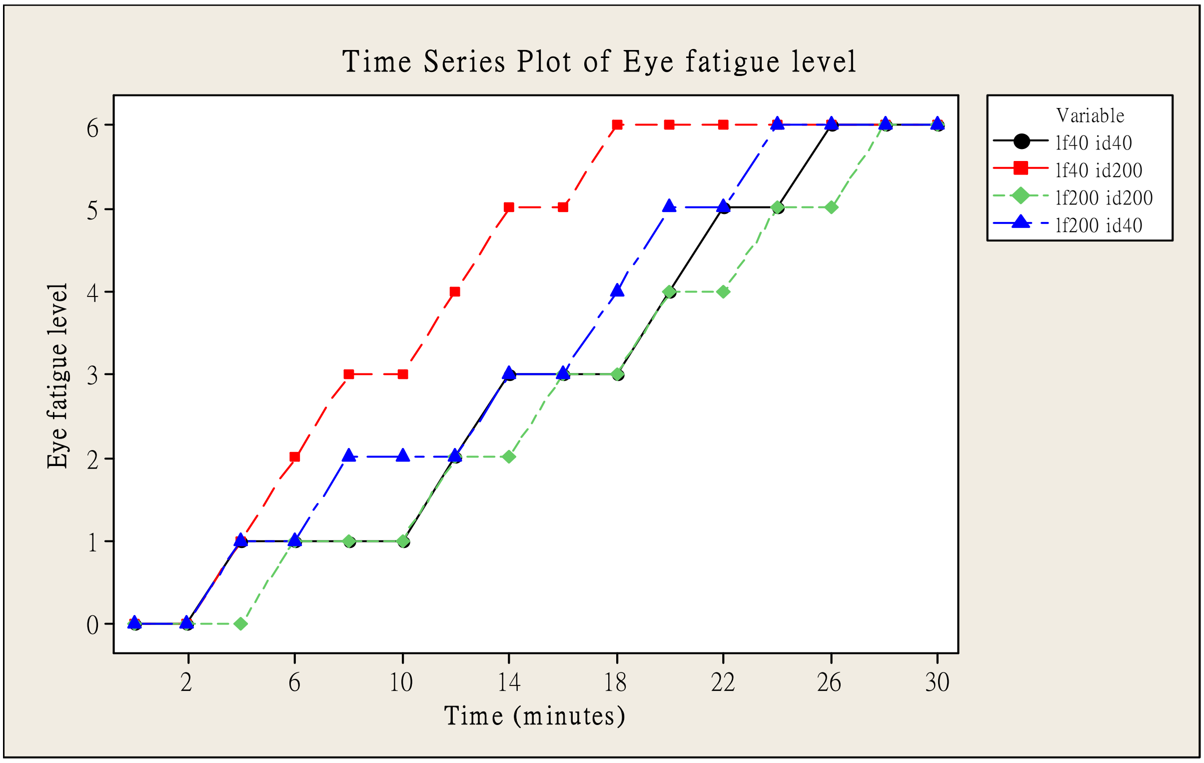

Figure A.12a Change of eye fatigue level over time for S12.

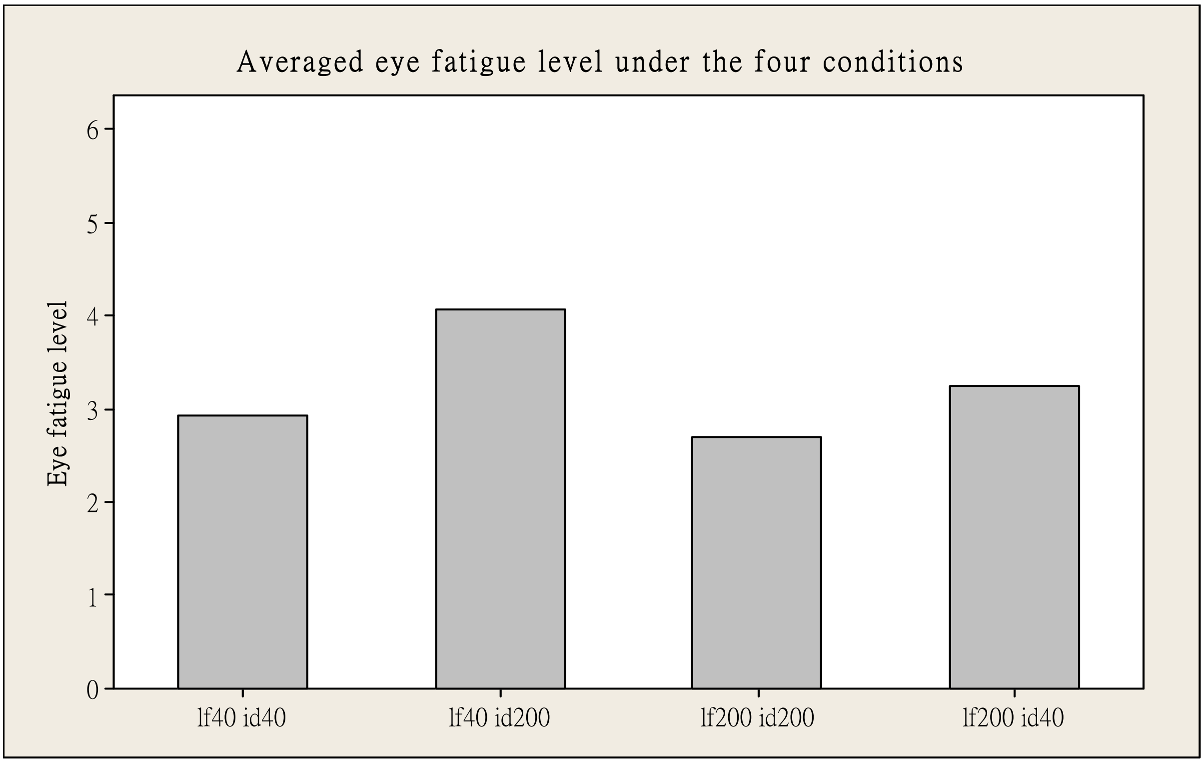

Figure A.12b Averaged eye fatigue level under the four conditions for S12.

APPENDIX B

ANALYSIS OF EFFECTS OF AGE

It was shown in section 2.3.2 that, the age was a significant factor in the ANOVA ($p < 0.0001$). Also, it was found that:

1. The interaction between age and lens focus was significant. ($p < 0.0001$)
2. The interaction between age and stereo depth was significant ($p < 0.0001$)

Since the interactions were significant, they may affect the result of test for hypothesizes H1 – H4. Therefore, interaction plots were drawn to find out the relationship of lens focus and stereo depth with age. (Figures B.1 – B.4)

Figures B.1 – B.4 show that there exists interaction between age and lens focus or stereo depth. However, the interaction was not of a meaningful one, and it may be due inter-participant variation.

Pearson correlation tests between age and eye fatigue level were conducted for the four conditions and the result is shown in table B.1.

Table B.1 Results of Pearson correlation tests used to test the correlation between age and eye fatigue level under the four viewing conditions.

Conditions	Pearson correlation coefficient	P-value
C1	-0.29975	0.3439
C2	-0.13841	0.6679
C3	-0.21119	0.51
C4	-0.07811	0.8093

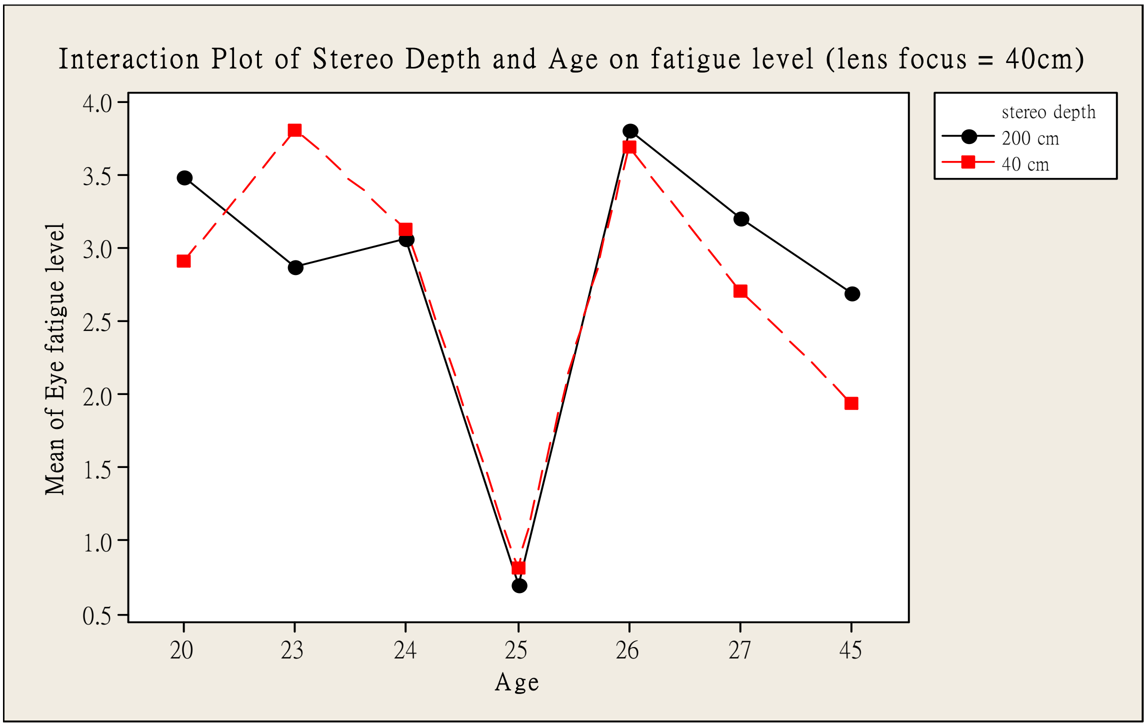

Figure B.1 Graph showing interaction between age and stereo depth under conditions appropriate for testing H1. (i.e. when lens focus = 40 cm)

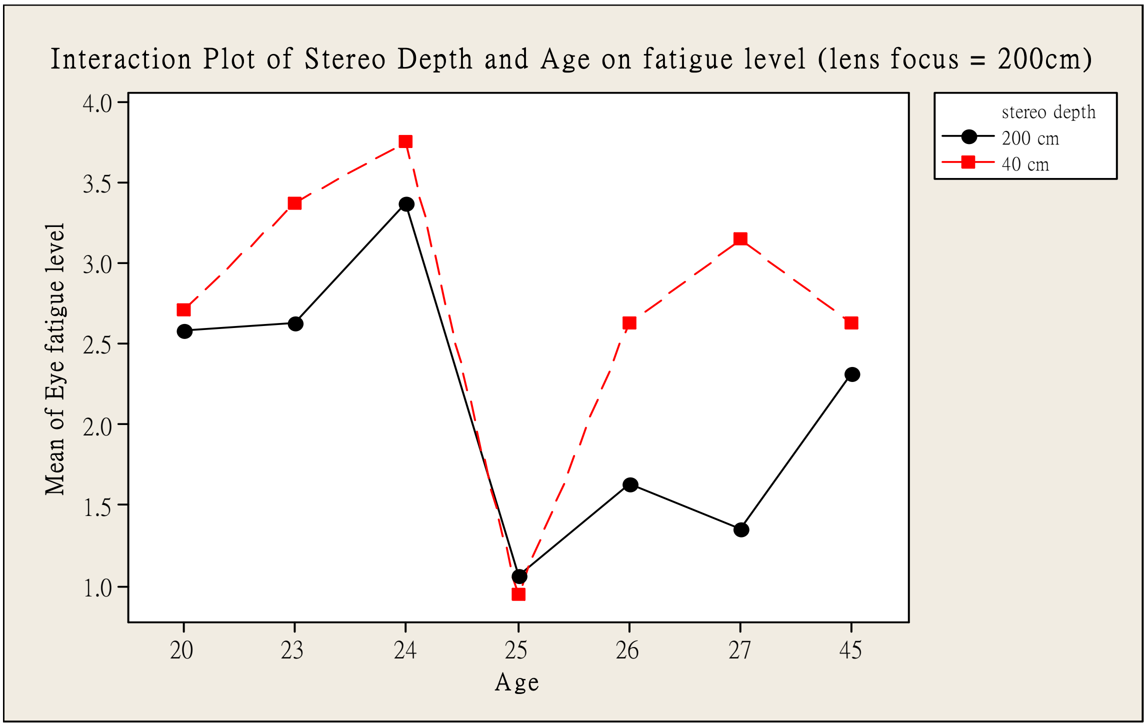

Figure B.2 Graph showing interaction between age and stereo depth under conditions appropriate for testing H2. (i.e. when lens focus = 200 cm)

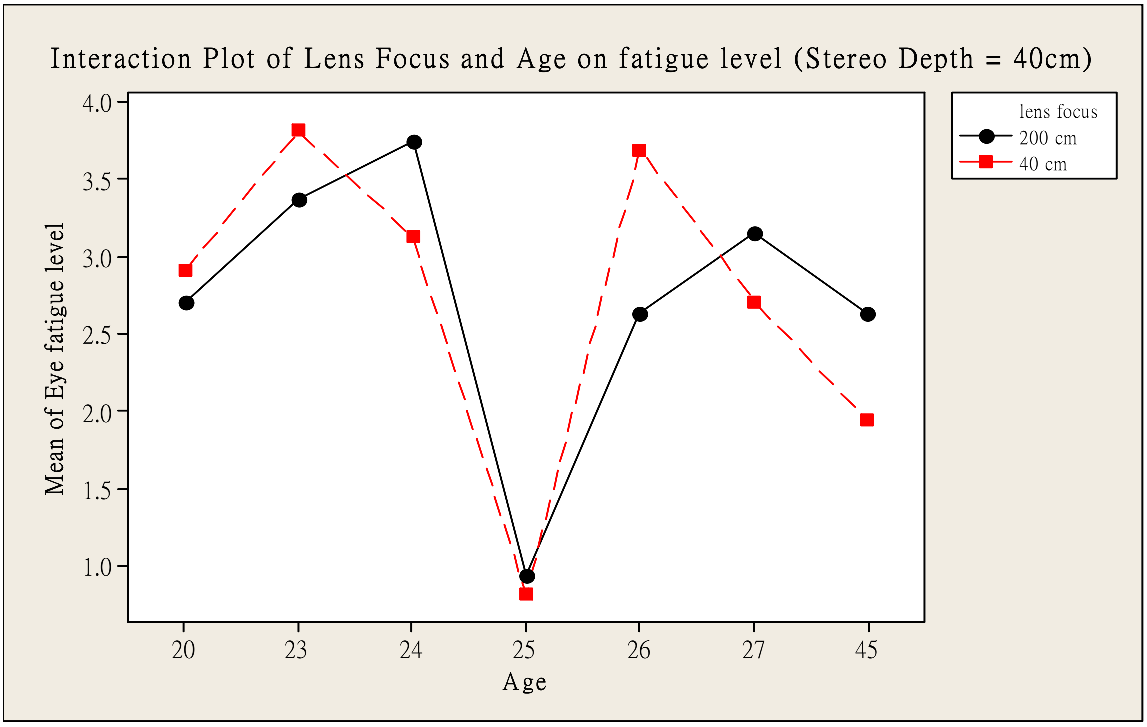

Figure B.3 Graph showing interaction between age and lens focus under conditions appropriate for testing H3. (i.e. when stereo depth = 40 cm)

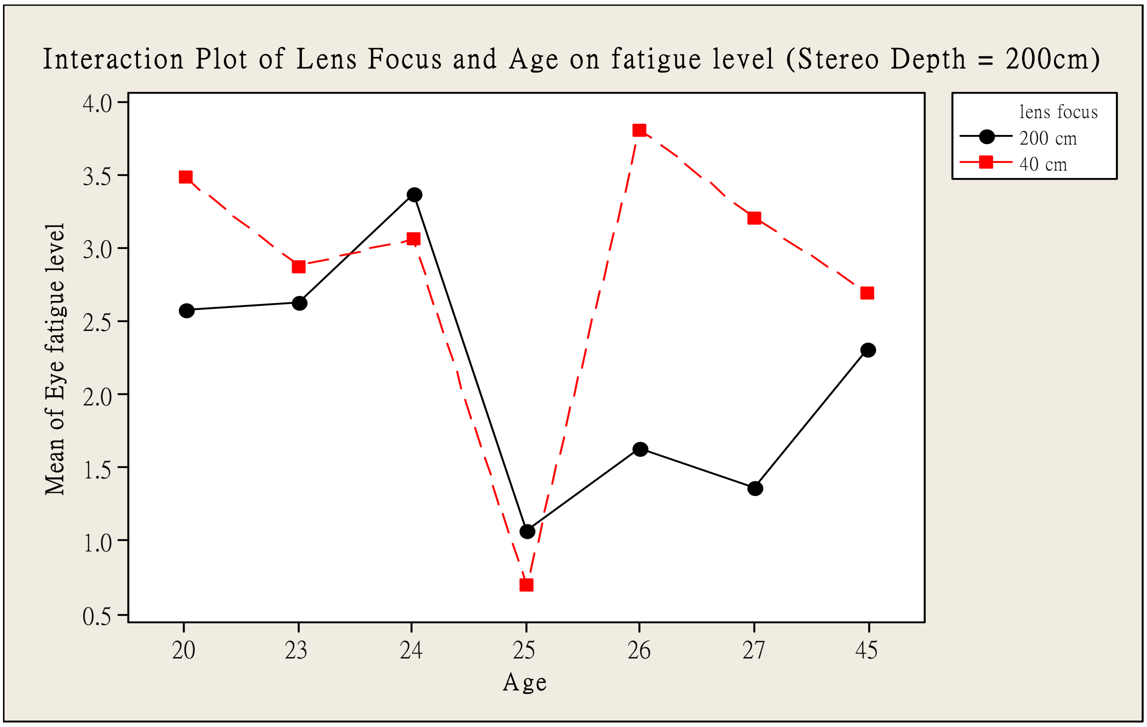

Figure B.4 Graph showing interaction between age and lens focus under conditions appropriate for testing H4. (i.e. when stereo depth = 200 cm)

Since all the p-values were larger than 0.1 in the correlation test, therefore, the age is not correlated with eye fatigue level under the four viewing conditions.

Pearson correlation tests between age and eye fatigue level were conducted for the four hypotheses. For instance, in hypothesis H1, the individual average eye fatigue data from conditions C1 and C3 were used for correlation test. The result is shown in table B.2.

Table B.2 Results of Pearson correlation tests used to test the correlation between age and eye fatigue level under the four hypotheses.

Hypothesis	Pearson correlation coefficient	P-value
H1	-0.25269	0.2335
H2	-0.10016	0.6415
H3	-0.19714	0.3558
H4	-0.15840	0.4597

Since all the p-values were larger than 0.1 in the correlation test, therefore, the age is not correlated with eye fatigue level under the four hypotheses.

From the tests above, it was concluded that there is no correlation between age and eye fatigue. Also, the interaction plots did not suggest a meaningful relationship between age and lens focus as well as age and stereo depth. Therefore the age, the interaction between age and lens focus, the interaction between age and stereo depth were taken out from the ANOVA model.

APPENDIX C

NEAR AND FAR VISUAL ACUITIES, STEREOACUITY, PHORIA AND AMPLITUDE OF ACCOMMODATION FOR EACH SUBJECT

Table C.1 Near and far visual acuities, stereoacuity, phoria of each subject.

Subjects Details			Far Visual Acuity (20 ft.)			Near Visual Acuity (14”)			Stereoacuity (in arc seconds)	Lateral Phoria (in prism dioptres)		Vertical Phoria (Far) (20 ft.) (in prism dioptres)
No.	Gender	Age	Both Eye	Right Eye	Left Eye	Both Eye	Right Eye	Left Eye		Far (20 ft.)	Near (14”)	
S1	M	27	20/17	20/18	20/20	20/15	20/13	20/18	40	2 (exo)	4.5 (exo)	0 (ortho)
S2	F	23	20/20	20/20	20/20	20/17	20/13	20/20	25	2 (exo)	3 (exo)	1/2 (left hyper)
S3	F	27	20/20	20/17	20/17	20/13	20/13	20/15	20	3 (exo)	1.5 (eso)	1/2 (left hyper)
S4	M	23	20/17	20/18	20/20	20/13	20/17	20/15	20	1 (exo)	0 (ortho)	0 (ortho)
S5	M	24	20/15	20/20	20/22	20/18	20/18	20/25	40	3 (exo)	7.5 (exo)	1/2 (right hyper)
S6	M	25	20/15	20/15	20/15	20/13	20/15	20/15	25	0 (ortho)	0 (ortho)	0 (ortho)

S7	M	20	20/17	20/20	20/18	20/15	20/13	20/15	40	3 (exo)	0 (ortho)	0 (ortho)
S8	M	20	20/18	20/25	20/30	20/15	20/20	20/15	20	3 (exo)	6 (exo)	1/2 (left hyper)
S9	F	26	20/20	20/25	20/22	20/20	20/20	20/22	25	1 (exo)	1.5 (eso)	1/2 (left hyper)
S10	M	45	20/17	20/18	20/20	20/17	20/20	20/20	20	3 (exo)	1.5 (eso)	0 (ortho)
S11	M	20	20/20	20/17	20/18	20/17	20/17	20/17	20	2 (exo)	3 (exo)	0 (ortho)
S12	M	20	20/17	20/20	20/18	20/13	20/20	20/15	40	4 (exo)	6 (exo)	0 (ortho)

Note:

A subject having a visual acuity of 20/20 (or equivalent to $20 \div 20 = 1$) is considered to have a normal vision.

A subject having a visual acuity lesser than 1 (e.g. 20/30 or 0.67) is considered to be poor than normal.

A subject having a visual acuity larger than 1 (e.g. 20/15 or 1.33) is considered to be better than normal.

eso = esophoria

exo = exophoria

ortho = orthophoria

hyper = hyperphoria

Table C.2 Amplitudes of accommodation measured from some subjects with their ages.

Subject	Age	Amplitude of Accommodation (dioptre)
S12	20	17.86
S11	20	14.62
S2	23	13.51
S8	20	12.1
S3	27	10.8
S7	20	10.44
S1	27	8.96
S6	25	8.53
S5	24	7.24
S10	45	2.32

Figure C.1 Vision tester used for testing near and far visual acuities, stereoacuity and phoria of each subject. (Model: OPTEC 2000, made in U.S.A.)

APPENDIX D

POTENTIAL APPLICATIONS OF THE RESULTS IN THIS STUDY

D1 Surgical training

Figure D.1 shows a surgeon wearing a HMD and performing a surgical training in a virtual environment. (Andries van Dam, Fuchs, Becker *et al*. 2002) The HMD shows to the surgeon, the body of the 'simulated' patient (see figure D.2). The HMD and the eye of the surgeon are separated at a distance to allow him to notice the situation in the surgical room. (e.g. nurse passing tools to the surgeon, etc.)

Figure D.1 A surgeon wearing a HMD and performing a surgical training in a virtual environment. Two micro-displays were installed inside the HMD for the surgeon to view the body of the 'simulated' patient.

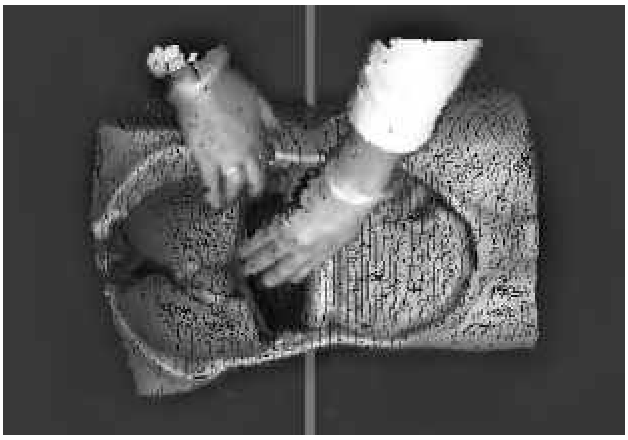

Figure D.2 The body of the ‘simulated’ patient.

The surgeon is usually required to perform surgery at a close distance, say around 40cm. While the lens focus of a typical HMD is fixed at 200cm. (See Appendix E for a list of lens focus of HMDs available in the market). This created a mismatched condition where stereo depth is smaller than the lens focus. Previous works by (Mon-Williams and Wann. 1998, Shibata *et al*. 2005) have suggested to adjust the lens focus to match with stereo depth to reduce eye fatigue experienced by the surgeon. However, results from this study suggest not to use adjustable lens focus because it makes no significant different when viewing images with stereo depth located at 40cm ± 0.3D. One solution to alleviate the eye fatigue problem is to create a target at stereo depth of 200cm so that the surgeon, after viewing images at stereo depth around 40cm for certain period of time, can see the target at 200cm to allow his eyes to take rest. In which, the stereo depth of the target is matched with the lens focus.

D2 Virtual Reality Exposure Therapy (VRET)

HMD can be used in psychological therapy in which a virtual environment is generated for the patient to experience a situation where they are afraid of being inside. Figure D.3 shows such kind of therapy, known as Virtual Reality Exposure Therapy (VRET). (C.A.P.G. van der Mast. 2006) It can be used to treat psychological problems such as: acrophobia (fear of height), fear of flying, claustrophobia (fear of enclosed space), fear of public speaking, fear of driving, posttraumatic stress disorder, agoraphobia (fear of open space), etc. Figure D.4 shows a virtual environment used for VRET.

Figure D.3 A photo showing a user wearing a HMD to experience a virtual environment which he is afraid of, this is a process of Virtual Reality Exposure Therapy (VRET).

Figure D.4 A snapshot of a virtual environment used for VRET.

The results in this study can be applied in VRET. Take treatment of claustrophobia (fear of enclosed space) as an example. Usually, users inside an enclosed space are viewing distance at near, say around 40cm. However, since typical lens focus of HMD is 200cm, a mismatch between lens focus and stereo depth results. Previous works by (Mon-Williams and Wann. 1998, Shibata *et al*. 2005) have suggested to adjust the lens focus to match with stereo depth to reduce eye fatigue experienced by the surgeon. However, results from this study suggest not to use adjustable lens focus because it makes no significant different when viewing images with stereo depth located at 40cm ± 0.3D. One method to reduce eye fatigue is to allow users to view distant image (e.g. ceiling at 200cm) periodically because matching of lens focus and stereo depth at 200cm can be achieved.

D3 Stereoscopic 3D games

One of the most common applications of HMD is gaming. Figures D.5a and D5b show snapshots of a stereoscopic game called “Rainbow Six Vegas 2 S-3D”. (Schneider. 2008)

Figure D.5a A snapshot of the stereoscopic video game: Rainbow Six Vegas 2 S-3D.

Figure D.5b A snapshot of the stereoscopic video game: Rainbow Six Vegas 2 S-3D.

In playing a stereoscopic video shooting game, both near and far stereoscopic images would be seen by the users. However, since lens focus of a typical HMD is 200cm and it was suggested in previous section (D1 and D2) that adjusting lens focus to match with far and near stereoscopic images is not good solution, another approach has to be proposed to reduce eye fatigue problem. From the results in this study, when lens focus is set at 200cm, viewing images with stereo depths varying within 40cm ± 0.3D (corresponding to the range 35.7cm - 45.2cm) is more fatigue than viewing images with stereo depths varying within 200cm ± 0.3D (corresponding to the range 125cm - 500cm). So, it is better to locate the target of a shooting game at a distance larger than 125cm as often as possible. Also, the game should be designed so that the users will not be viewing stereoscopic images varying within 40cm ± 0.3D continuously for a long period of time, say, for instance, more than 10 minutes.

APPENDIX E

TYPICAL LENS FOCUS OF HMDS IN THE MARKET

Table E.1 A list of typical lens focus of HMDs in the market with brand names and models.

Brand Name	**Model (Year)**	**Lens Focus (cm)**
Virtual Research[1]	V8 (1998)	91.44
iMD[2]	iSDTV (2004)	200
CyberMind[3]	Visette45 SXGA (2008)	200
Vuzix[4]	iWear AV920 (2005)	274.32
eMagin[5]	Z800 3D Visor (2005)	365.76
CyberMind[6]	hi-Res800 (2003)	396.24
IO Display Systems[7]	i-glasses PC/SVGA Pro 3D (2005)	396.24

Reference Manual or Web site:

1. V8 User Guide, *Virtual Research Systems, Inc*.
   http://www.virtualresearch.com/Acrobat_files/V8MANUAL.PDF
2. iSDTV704C microdisplay, *Integrated Microdisplays Limited (iMD)*.
   www.hkimd.com/microdisplay/isdtv704c_brief.pdf
3. Visette45 SXGA, *Cybermind Interactive Netherlands*.
   http://www.cybermindnl.com
4. iWear AV920, *Vuzix*.
   http://www.vuzix.com/iwear/products_av920.html
5. eMagin Z800 3DVisor, *eMagin Corporation*.
   http://www.emagin.com/products/systems/Z800.php
6. hi-Res800, *Cybermind Interactive Netherlands*.
   http://www.cybermindnl.com
7. i-glasses PC/SVGA Pro 3D, *IO Display Systems*.
   http://www.i-glassesstore.com/iglassespc-3d.html

APPENDIX F

GLOSSARY OF TERMS

Depth of focus (DOF)

If the eye is focused for a given distance, then an object either nearer or farther away will produce a blurred image on the retina. Within a certain range (i.e. the depth of focus), the observer is unable to detect this blurring and any object within this range will be perceived with maximum visual acuity.

Inter-pupillary distance (IPD)

The inter-distance between the centre of the left and right pupils of the eyes.

Lateral phoria

Phoria, or called hetereophoria, is a latent squint. It was a condition of motor imbalance of the eyes.

There are two types of lateral phoria: esophoria and exophoria. Esophoria means the eyes have a tendency to deviate nasally. Exophoria means the eyes have a tendency to deviate temporally.

Orthophoria

Expected or normal teamwork of the eyes in which ocular balance is achieved. That is, the eyes do not tend to deviate in any direction.

Stereoacuity

A measure of minimum perceivable difference in stereo depth.

Vertical Phoria

Phoria, or called hetereophoria, is a latent squint. It was a condition of motor imbalance of the eyes.

There are two types of vertical phoria: hyperphoria and hypophoria. Hyperphoria means one eye have a tendency to turn upwards relative to another eye. Hypophoria means one eye have a tendency to turn downwards relative to another eye.

Visual Acuity

A measure of the ability of eyes to resolve or discriminate spatially organised detail.