The effects of matching lens focus with stereoscopic depth cues on the time taken to form a single stereoscopic image when viewing a binocular display: system prototyping and experimentation

by

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This is to certify that I have examined the above MPhil thesis
and have found that it is complete and satisfactory in all respects,
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the thesis examination committee have been made.

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The effects of matching lens focus with stereoscopic depth cues on the time taken to form a single stereoscopic image when viewing a binocular display: system prototyping and experimentation

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Abstract

Human eyes see the same object from slightly different viewpoints. Unless the object is placed at infinity, our eyes have to verge towards each other in order to fixate on the same object. Such vergence eye movements are also coupled to appropriate accommodation changes of our eyes in order to focus on the object. Unfortunately, this coupling is disturbed when viewing current binocular displays. On binocular displays, images with correct stereoscopic depth cues can be presented to induce appropriate vergence eye movements. However, the lens focus of such displays is typically fixed regardless of changing depth cues. This posts an un-natural demand on the viewer's eyes since the viewing condition demands vergence movement in the absence of appropriate accommodation changes. This thesis studies, for the first time, the effects of matching lens focus with stereoscopic depth cues on the time taken to form a single stereoscopic image when viewing a binocular micro-display. A micro-display system with dynamically adjustable lens focus was designed and prototyped for this study. The design and prototyping work forms part of the contribution of the thesis. An experiment was then conducted to study the time taken to merge a pair of left and right binocular images into a single stereoscopic image under four viewing conditions that exhaust the combinations of two lens focus (40cm and 200cm) and two object depths (40cm and 200cm).

Results indicate that viewers took significantly shorter time to form a single overlaid stereoscopic image when the lens focus matched with the object depth ($p<0.05$, paired t test). Further examinations of the data suggest that unnatural demand for the eyes to diverge (e.g., lens focus was smaller than the object depth) are associated with significantly longer periods of double images.

Among the ten viewers, seven consistently and significantly benefited from the effect of matching lens focus with stereoscopic depth cues but three viewers did not. The relationships between individuals' performance in the study and their visual parameters have been studied. Significant correlations are found between the time taken to form a single stereoscopic image and the negative fusional reserve of the participants. The work of this thesis evaluates the potential benefits of applying dynamically adjustable lens focus to the future design of binocular micro-displays.

1 Introduction

1.1 Overview

1.1.1 Conventional Micro-display Systems

A conventional micro-display system mainly consists of a liquid crystal display (LCD) screen, a set of magnifying lens, and the associated electronics. The design of the optics of a micro-display system allows viewers to see clear magnified virtual images when their eyes are placed close to the displays. Since the micro-display system is small and light (typical less than 1kg), the system can be head-mounted.

Most typical micro-display systems only provide fixed lens focus. They can be classified into two groups. For one group, the lens is mounted and fixed on the micro-display system. Since the inter-distance between the micro-display screen and the lens is fixed, the lens focus of these systems is therefore fixed. This is further explained in Chapter 3.

Fig 1.1. Two examples of binocular micro-display systems. Left side is a V8 head mounted display from Virtual Research Systems, Inc. Right side is a spectacles-formed micro-display system from Integrated Microdisplays Limited (iMD). From the manufacturers' information, V8 has a fixed lens focus of 3 ft (91cm) and the one from iMD has a fixed lens focus of 2m.

For the other group, the positions of the magnifying lens can be slightly adjusted manually. The purpose is to slightly adjust the inter-distance between the micro-display screen and the lens so that the lens focus can be changed. This is convenient for users with myopia or hyperopia where users can view the micro-display images sharply without corrective spectacles. However, in this group, the lens focus is not supposed to be adjusted when the users are viewing the micro-display. In other words, during operation, this kind of micro-display system still provides fixed lens focus only.

1.1.2 Binocular Micro-display Applications at Virtual Environments

Furthermore, a binocular micro-display system can allow viewers to have depth perception on objects displayed by binocular images. This makes binocular micro-display systems widely used in virtual reality applications for various purposes including industrial, training and entertainment.

1.1.3 How a Viewer Forms a Single Stereoscopic Image at a Binocular Micro-display

The principle of forming a single stereoscopic image is briefly introduced here. In viewing the natural world, suppose the object of interest is located at a certain distance away from the viewer, but not at infinity. If the viewer's eyes look straight, the viewer will find that the objects seen by the left and right eye are at different horizontal positions. The horizontal position difference, referred to as horizontal disparity, depends on the depth of the object, which is the distance between the object and the viewer. The relationship between the horizontal disparity and the depth of the object is inversely proportional. The nearer the object to the viewer (i.e.

the smaller the depth), the larger the horizontal disparity. People are able to form a single stereoscopic image at the object of interest by appropriately turning the eyes inward (convergence) such that the horizontal disparity of the objects gradually reduces, until it becomes so small that the visual system within the brain can merge the objects on the left and right images into one single object. In other words, a single stereoscopic image is formed.

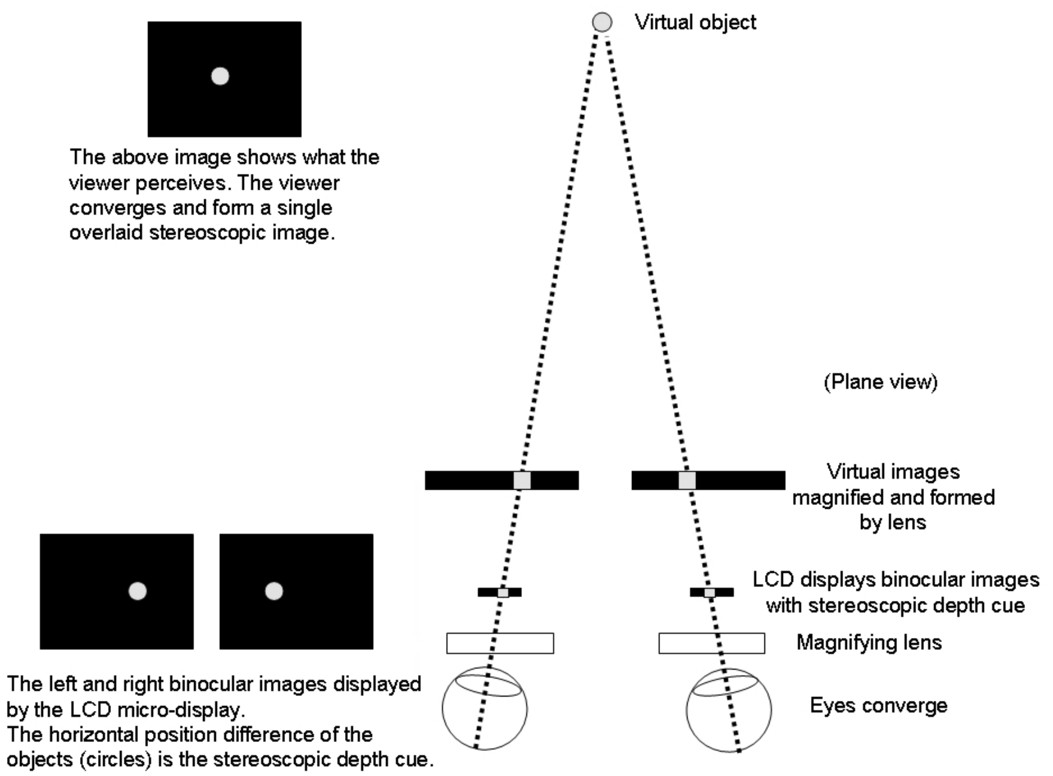

Fig 1.2. A diagram showing how a viewer forms a single overlaid stereoscopic image when viewing a binocular display. On the right side there is a plane view of the schematic configuration of a conventional micro-displays system with LCD micro-display screens and magnifying lens. Two LCD screens display binocular images with stereoscopic depth cues as shown at the bottom left corner. The lens magnifies the tiny micro-display image into a magnified virtual image.
The viewer converges and fixates at the object of interest, and as a result form a single overlaid stereoscopic image. The image at the top left corner shows what the viewer perceives.

With the binocular micro-display system, the left and right LCD screens display binocular images in which the objects shown in the left and right images have horizontal disparity. These are stereoscopic depth cues that geometrically determine the depth of the virtual object. This stereoscopic depth cues require the viewer to utilize vergence to fuse the virtual object. The viewer can then form a single stereoscopic image on the object.

1.1.4 Lens Focus and Stereoscopic Depth Cues (Object Depth)

There are two important parameters in a binocular micro-display system, i.e. lens focus and object depth. In this thesis, lens focus is referred to as the distance between the magnified virtual image and the lens. This is the image distance of the magnified virtual image. The use of the term "lens focus" is related to the magnifying lens of the micro-display system. The lens focus is determined by the focusing power of the magnifying lens and the inter-distance between the magnifying lens and the LCD screen.

Stereoscopic depth cues geometrically determine the depth of the virtual object. The depth of the virtual object can be abbreviated as "object depth". Since object depth is geometrically determined by the stereoscopic depth cues in the left and right binocular images, it should be aware that object depth is an exact dimension. Stereoscopic depth cues, or object depth, are objective. It is different from the depth perception within a person's brain which is subjective.

In this thesis, the shorter term object depth is frequently used, especially in the sections that present the experiment findings. The term object depth shares the same meaning as stereoscopic depth cues.

1.1.5 Specialized Terms in the Thesis

Besides lens focus and stereoscopic depth cues, other specialized terms in the field of virtual reality, binocular display and visual system are used. A glossary of terms, presented in the Appendix, is prepared for the readers to enhance their understanding on the thesis.

1.2 Problem Statement

1.2.1 Human Factors Drawbacks on the Visual system

When viewing the natural world, people need not only accommodation (changing of the lens' thickness of the eye) to see an object sharply, but also vergence to fuse the object. People then adapt the proportional relationship between accommodation and vergence. The more the eyes accommodate, the more the eyes converge.

Nowadays most typical micro-display systems only provide fixed lens focus. At a binocular display condition where the objects have different and changing depths, the fixed lens focus of the micro-display leads the viewer to focus at a fixed distance, i.e. accommodation becomes constant. The eyes then need to verge to different extents in order to form a single stereoscopic image at the objects that have different depths which are not the same as the accommodation distance. The viewers are forced to verge without respective accommodation actions. This action violates the relationship between accommodation and vergence as in natural world viewing (Rushton and Riddell, 1999).

This conflict between accommodation and vergence is thought to be the cause of various side effects of using binocular micro-display images, for example cybersickness and visual fatigue (Wann et al. 1995, 1998).

1.2.2 Possible Difficulty in Forming a Single Stereoscopic Image

Besides the unpleasant symptoms, it is possible that some viewers may find difficulty verging without respective accommodation actions. This will affect the time to form a single stereoscopic image (referred to as single image formation time in the latter sections). If the micro-display applications involve this scenario, this problem will affect viewers' performance e.g. slow response, or even failure to perform, since only double images are perceived. These degrade the usability and functionality of these applications.

1.2.3 The Need of a Possible Solution: Matching Lens Focus with Stereoscopic Depth Cues

If the cause of the problem is the conflict between accommodation and vergence, then the direct solution is to eliminate this conflict. If lens focus is the same as object depth, the accommodation distance (influenced by the lens focus) should be the same as the convergence distance (influenced by the stereoscopic depth cues). This means the conflict should be eliminated.

Matching lens focus with stereoscopic depth cues means the two parameters are set to be the same. As stereoscopic depth cues carry the depth information of the virtual objects, it cannot be modified in order to match, i.e. be same as, the lens focus. Obviously, changing lens focus to match with the stereoscopic depth cues is the feasible choice.

There are some studies dealing with the elimination of this conflict. Rolland et al (2000) proposed the approach of multi-focal planes head-mounted displays to suppress the conflict between accommodation and vergence. In their head-mounted display system, they used a number of equally spaced planes at the display and a fixed magnifying lens. The illumination of the pixels on the different planes led to a variation of inter-distance between the illuminated plane and the lens, so that the image distance (i.e. lens focus) could be adjustable to match with the virtual depth of the object.

There has been research that used the approach of changing the inter-distance between the display and lens by directly moving the display closer or further away from the viewer. Shibata et al (2004) reported a study on the visual response of viewers when they viewed a binocular display. This display was not a micro-display and did not consist of a magnifying lens. At the experiment set-up, the stereoscopic display screen moved fore and aft so that the viewing distance was adjusted and matched with the stereoscopic depth cues. The real-time visual measurements result during viewing indicated that when the image distance (i.e. lens focus in the case of micro-display system) matched with the stereoscopic depth cues, the deviation between accommodation and vergence was largely reduced.

1.3 Research Gap

1.3.1 Literature Review: Shows Relevant Studies to the Proposed Solution are Limited

The motivation of this study is to further the understanding in the area of single image formation time at binocular micro-display. Literature on this topic is sparse. There have been very few relevant studies on the single image formation time appearing in the field of visual science, and virtually no research into the effects on the single image formation time at binocular display. In short, the factors on the single image formation time are not well studied.

1.3.2 Research Gap

The approach of matching lens focus with stereoscopic depth cues to eliminate the conflict of accommodation and vergence has been adopted and applied by some researchers (Rolland, 2000; Shibata et al, 2004) in their studies and applications. However, they were either not verified by human experiments or their studies only focused on unpleasant symptoms and visual measurements, and they did not reach the area of single image formation time. The study in this thesis aims to examine the proposed solution of matching lens focus with stereoscopic depth cues with regard to the single image formation time.

1.3.3 Scope of the Study

The experiment task involved the transition of biocular (identical) images to binocular images. Participants formed a single stereoscopic image at binocular images starting from the state of perceiving single image at biocular images. This simulated the fixation at far objects and near objects alternatively, and the switching of biocular and binocular images at real applications. In the experiment task, the objects (3-D texts) were stationary. This simulated a reading task. The scope of the study limits to the single image formation time at the static condition of lens focus and stereoscopic depth cues. The lens focus and stereoscopic depth cues would not change within an experimental condition.

1.4 Research Objectives

1.4.1 Study the Benefits of Matching Lens Focus with Stereoscopic Depth Cues on the Time Taken to Form a Single Stereoscopic Image

This is the major objective of this study. Through this study, the understanding on the effect of matching lens focus with stereoscopic depth cues on the area of single image formation time can be enhanced.

1.4.2 Prototype a Micro-display System with Dynamically Adjustable Lens Focus

Since a micro-display system with dynamically adjustable lens focus is not commercially available, one with dynamically adjustable lens focus has been designed and prototyped for the experiment. Besides experimental use, the design and prototyping process demonstrated the feasibility of developing the dynamically adjustable lens focus and to experience the difficulties such as design constraints and technical limitations through the design and production process.

1.5 Thesis Outline

Chapter 1 mainly introduces the fundamentals of a binocular micro-display system and the formation of a single stereoscopic image. The problem, research gap and research objectives are presented. Chapter 2 presents some background information of the topic and the related studies. Chapter 3 presents the design and prototyping of a dynamically adjustable lens focus micro-display system. Chapter 4 presents the design of experiment of this study. Chapter 5 presents the analyses of the experimental results. Chapter 6 studies the variation of the individual participants' response and the relationship between the response and their visual parameters. Finally, Chapter 7 discusses and concludes this study.

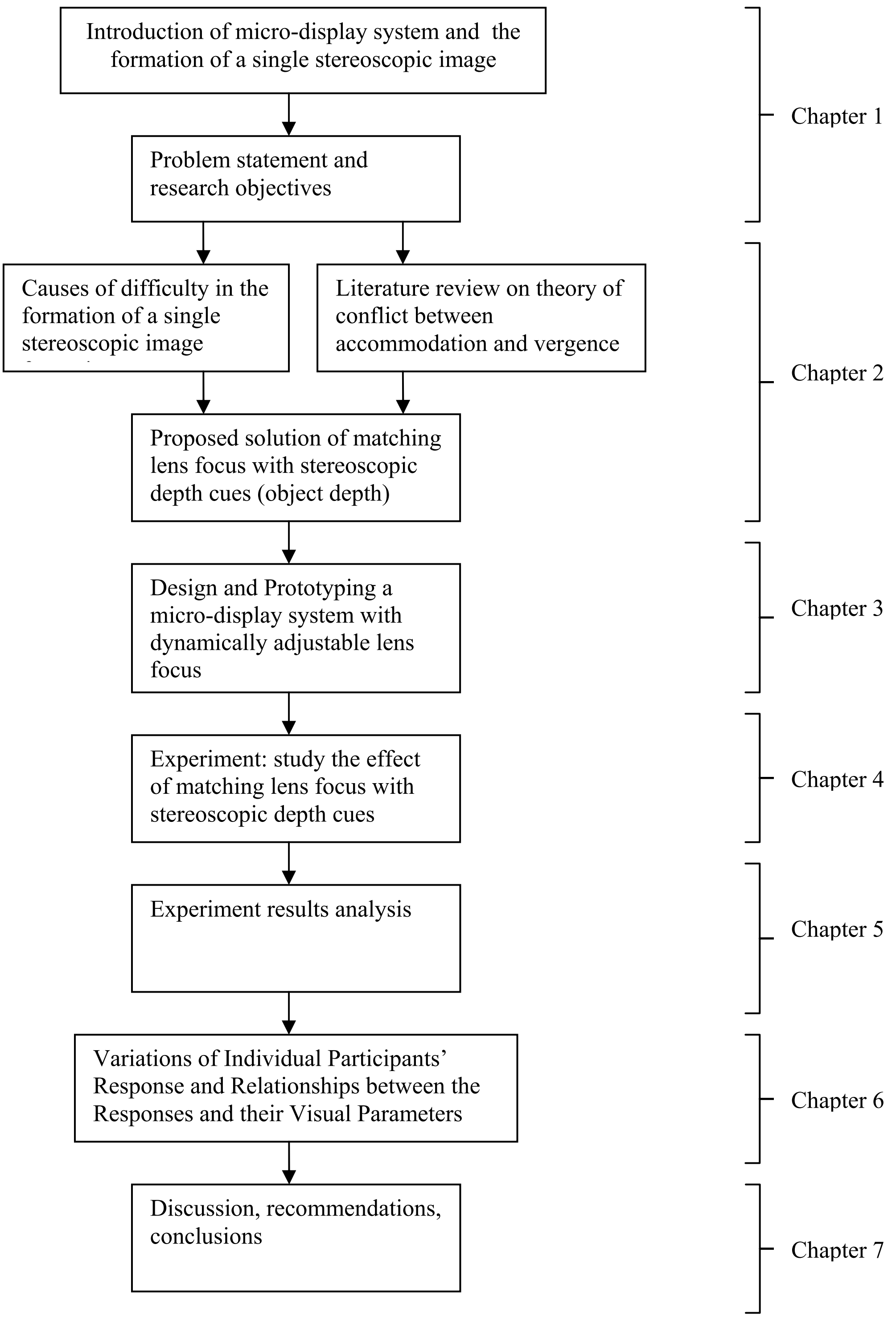

Fig.1.3 Outline of the thesis

2 Background

2.1 Difficulty in Forming a Single Stereoscopic Image When Viewing a Binocular Micro-display with Fixed Lens Focus

2.1.1 Ocular Processes Involved in Forming a Single Stereoscopic Image

As explained in Chapter 1, when viewing a fixed lens focus binocular micro-display system, if the object of concerned has an object depth different from the lens focus, viewers are forced to verge without the appropriate accommodation action. Normally, a viewer can handle this but the ability to converge without the appropriate accommodation action will depend on the viewer's positive fusional convergence ability. Conversely, if a viewer needs to diverge without the appropriate accommodation action, negative fusional convergence ability is needed.

For example, if the lens focus is set to 200cm. A viewer will accommodate all objects at 200cm and consequently will verge their eyes at a virtual depth of 200cm in appropriate to the accommodative actions. However, if the viewer is required to view an object at a virtual depth of 100cm, the viewer will perceive double images on that virtual object. Then, the horizontal disparity between the objects seen by the left and right eyes will generate a fusional cues and the viewer's eyes will further converge from 200cm to 100cm so that a single stereoscopic image is formed. The time taken to switch from double images to a single image will be referred to as the single image formation time in this study.

On the other hand, say the lens focus is maintained at 200cm and now the viewer wants to form a single stereoscopic image on a virtual object with a depth 300cm.

This time the viewer, because of the fusional cues, uses the negative fusional convergence ability to diverge from 200cm to 300cm.

2.1.2 Literature Review on the Problem in Forming a Single Stereoscopic Image

Eichenlaub (2005) described the problem of inability to fuse images, in other words the difficulty in forming a single stereoscopic image under the case of conflict between accommodation and vergence. It was pointed out that the problem was especially strong in situations of head mounted virtual reality displays (an application of binocular micro-display) since the virtual objects were displayed across a large range of depth. The author used several cases to illustrate the problem. For example, in a situation where the lens focus of the head-mounted display is often between six feet (around 1.8m) and infinity, where viewers need to converge their eyes to form a single stereoscopic image on a virtual object that was far closer or much further away from that accommodation distance, "eyestrain may occur or double images may be perceived" (p.517).

Before Eichenlaub described the cause of the inability to fuse images was related to the conflict of accommodation and vergence, the occurrence of the conflict of accommodation and vergence at stereoscopic head mounted display has long been recognized (Roscoe, 1987, 1988; Wann et. al. 1995, 1997)

2.2 The Proposed Solution: Matching Lens Focus with Stereoscopic Depth Cues

2.2.1 Description of the Solution

In the earlier sections, it is stated that when the fixed lens focus does not match with the stereoscopic depth cues, this causes a conflict between accommodation and vergence. The conflict then causes the difficulty in forming a single stereoscopic image.

The works of Rolland and Shibata which attempted to solve the conflict between accommodation and vergence have been mentioned in Chapter 1. Basically, they utilized different methods to make the lens focus or image distance matches with the stereoscopic depth cues. This approach of varying the object distance so as to alter the image distance was the common approach.

2.2.2 Elimination of the Conflict between Accommodation and Vergence

However, can the matching between lens focus and stereoscopic depth cues effectively eliminate the conflict of accommodation and vergence? The work of Shibata (2004) gave a preliminary answer. In an experiment in which the stereoscopic depth range was between 40cm and 200cm, the real-time visual measurements that resulted during an experimental viewing task indicated that when the image distance (i.e. lens focus in the case of micro-display system) matched with the stereoscopic depth cues, the accommodation distance and convergence distance of the participants appeared to be very similar throughout the experiment process. Their data suggested that the matching of lens focus with stereoscopic depth cues can successfully eliminate the conflict of accommodation and vergence. However, they did not study the time taken to form a single stereoscopic image.

Shibata's results supports that the need of our study. In the next chapter, the system prototyping of a dynamically adjustable lens focus micro-display is presented.

3 Prototyping of a Dynamically Adjustable Lens Focus Micro-display

3.1 Design

3.1.1 Design Objective

Typical micro-display systems provide only fixed lens focus (see Chapter 1). These displays only provide one level of lens focus which is not enough for the current study. This study requires a binocular micro-display that can provide automatically real-time adjustable lens focus.

To cater to the needs of this study, a dynamically adjustable lens focus micro-display system has been designed, developed, and prototyped. The main purpose is to develop a working prototype that can fulfill the requirements of the experiment so that the effect of matching lens focus with stereoscopic depth cues can be studied.

The development work focuses on the area of dynamically adjustable lens focus since this is not currently available in the market. The approach of the system prototyping is to select and utilize commercially available micro-display units that can fulfill the requirements of the experiment. Then the dynamically adjustable lens focus module is designed according to the specifications of the micro-display units. After that, the dynamically adjustable lens focus module will be assembled onto the micro-display units and formed into a complete dynamically adjustable lens focus micro-display system.

The micro-display units is supplied by Integrated Microdisplays Limited (iMD), Hong Kong, PRC. The model is iSDTV704C and has fixed lens focus only. 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 specific design objective is to supply a dynamically adjustable lens focus module which can be assembled on the iMD iSDTV704C micro-display unit and can fulfill the requirements of the experiment.

3.1.2 The Lens Focus Adjustment Principle

As mentioned in Chapter 1, lens focus is the virtual image distance. Lens focus is determined by the object distance (i.e. the inter-distance between the micro-display screen and the magnifying lens) and the focal length of the magnifying lens (i.e. the lens focusing power).

With reference to the lens formula, the relationship of lens focus, object distance and focal length of the lens can be described by:

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

Where

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

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

f = focal length of the magnifying lens

The formula can be rearranged as

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

It can be seen that the adjustment of lens focus (v) can be achieved by changing the distance between the micro-display screen and the magnifying lens (u), or changing the focal length of the lens (f). The first method was mentioned by Melzer and Moffitt in 1997.

The conventional micro-display systems which allows the change of image distance to facilitate both myopic and hyperopic viewers are surveyed and it is found that there are systems that achieve the change of image distance by moving the lens towards the micro-display screen, or moving outwards from the screen. An example is the iSDTV micro-display system from iMD. (It should be noted that this is manual adjustment only before the micro-display system is being viewed at. When the micro-display system is in used and is being viewed at, the lens focus remained fixed.)

Based on the fact that the method of changing the distance between the micro-display screen and the magnifying lens has been applied to existing products and furthermore this method is relatively easier to achieve than dynamically changing the lens focal length, in this system prototyping, the method of changing the distance between the micro-display screen and the magnifying lens is applied to adjust the lens focus.

3.1.3 Design Criteria for the Micro-display Used in the Experiment

In order to successfully match the dynamically adjustable lens focus model onto the micro-display unit, the structure and the dimensional specification of the micro-display unit should be considered. The iSDTV704C micro-display system consists of two liquid-crystal-on-silicon (LCoS) micro-display as the display panels. The display area is 0.56" diagonally. A polarized beam splitter is placed between the display panel and the outer surface of the lens and this takes up a length of about 20mm.

These form two major design criteria. The first criterion is the lens used in the dynamically adjustable lens focus module have to be large enough to allow the viewer to view the complete display area. The second criterion is the polarized beam splitter constrains the position of the lens of the dynamically adjustable lens focus module. These two criteria determine the selection of lens parameters such as lens diameter, size and focal length.

3.1.4 Design Criteria for Precise Lens Focus Adjustment

Precision lens focus adjustment represents the accuracy and precision of the lens focus level. As in the design, the lens focal length can not change, therefore this design criteria can be transformed into the precise adjustment of the object distance adjustment.

There are two reasons for the requirement of precise lens focus adjustment. Firstly, precise lens focus adjustment can provide flexibility to match with the different and variable levels of stereoscopic depth cues. Secondly, and even more importantly, with reference to the relationship between lens focus, object distance and lens focal length: v = (u*f) / (f-u), it can be observed that lens focus has a quadratic relationship with object distance (since focal length f was fixed). Simply speaking, when object distance becomes larger, lens focus increases. Also, when object distance is large, every unit change of object distance will largely increase the lens focus. It is necessary to maintain the precision of lens focus adjustment at the far region (say when lens focus is at the range from 1m to infinity).

In the subsequent sections in this chapter, the precise object distance adjustment will be described.

3.1.4.1 Optical Design

After considering the design criteria, it was aimed to design an optical system which provided a range of lens focus adjustment from 40cm to optical infinity. The field-of-view was 30 degree in diagonal.

Though the typical near point of human eye is 25cm (i.e. the nearest distance that the eye can accommodate to and see a sharp image), due to space limitation (constrained by the polarized beam splitter) the object distance could not reduce to the extent so that the lens focus became 25cm. In the experimental design introduced in Chapter 4, the near stereoscopic depth cues was chosen to be 40cm. Therefore the range of lens focus having a lower limit of 40cm could fulfill the experiment requirement.

Mentioned in Section 3.1.2, by positioning the lens at the appropriate position, the desired lens focus could be obtained. Schematic diagrams were presented to illustrate this method.

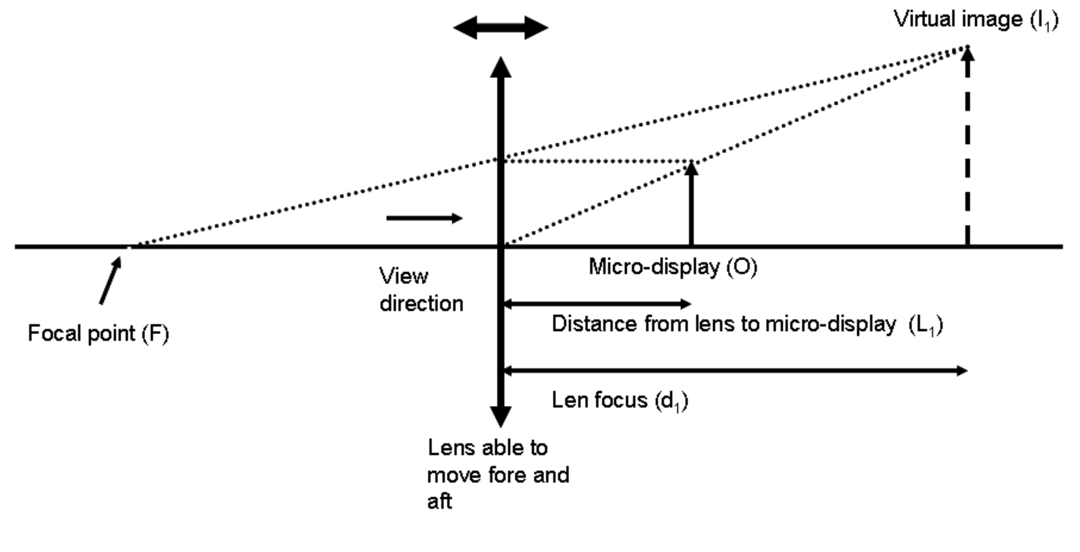

Fig 3.1. A schematic diagram showing the formation of a virtual image at the prototype micro-display system. The simplified configuration of the system is shown. Not all units of the micro-display system are drawn, e.g. polarized beam splitter.

Figure 3.1 shows the simplified configuration of the dynamically adjustable lens focus micro-display system in the system prototyping design. Some units, e.g. polarized beam splitter, are not drawn. The components are represented by symbols. For example the lens, for simplicity it is represented by a double arrow symbol.

The below schematic diagram shows that when the lens is suitably located in front of the micro-display screen, the lens will magnify the micro-display image into a virtual image. The distance between the micro-display screen and lens should be equal or smaller than the lens focal length in order to obtain a magnified virtual image. When the distance between the micro-display screen and lens equals the focal length, the lens focus will become infinity.

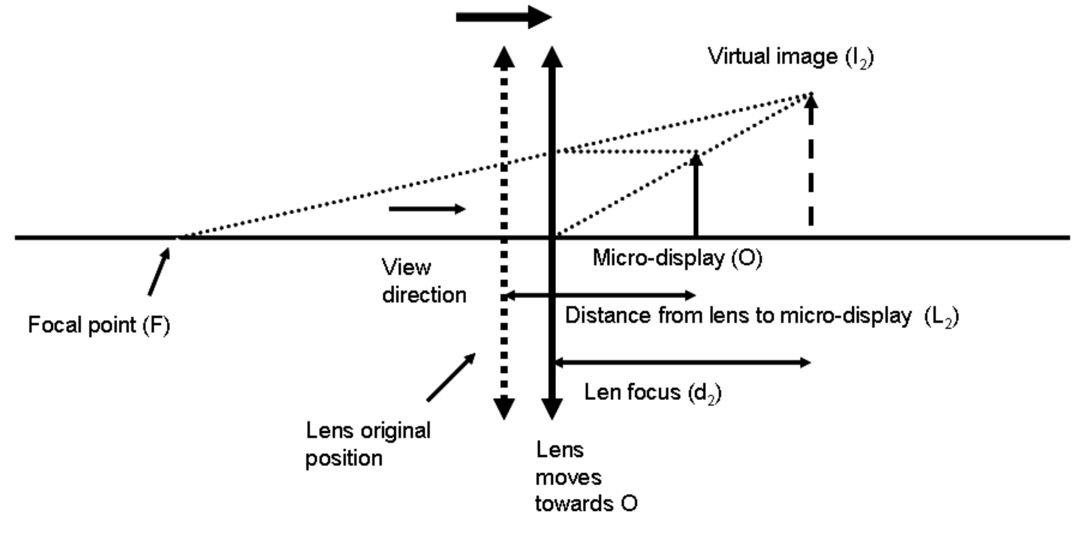

Fig 3.2. A schematic diagram showing how the change of the distance between the micro-display screen and the lens can change the lens focus.

Fig 3.2 illustrates how the change of object distance varies the lens focus. In the figure, the lens moves towards the micro-display (O). The distance from the lens to the micro-display (object distance) is reduced from L_1 to L_2. Then it can be seen that the lens focus decreases from d_1 to d_2. The closer the lens to the micro-display, the smaller the lens focus. In the prototype system, to bring the lens focus from infinity to 40cm, the lens movement distance is around 2mm.

3.1.4.2 Mechanical Parts that Drive the Lens

The inward and outward movement of the lens was achieved through a screw and thread design. The lens was held by a lens fixture which had an external thread (a male part). A lens adapter (a female part), which had an internal thread on its wall surface, allowed the lens fixture to screw in. One revolution of the lens fixture corresponded to a lens movement of 0.5mm to or from the micro-display screen.

The movement of the lens was driven by a stepper motor via gear arrangements. Gears were mounted to the lens and the stepper motor, and both gears were engaged.

The gear ratio was 1:1, i.e. one revolution of stepper motor would lead to one revolution of lens.

A microcontroller unit (MCU) was used to control the turning of the stepper motor and thus controlled the position of the lens. The angular displacement for each step of the stepper motor was 1.8 degree. In order for the stepper motor to turn one revolution, (360 degree) / (1.8 degree/step) = 200 steps were needed.

Therefore the stepper motor turning of one step change could move the lens position by 0.5mm / 200 step = 0.0025mm/step. The precise lens movement meant that the distance between the micro-display screen and lens could be finely adjusted. This fulfilled the design criteria for precise lens focus adjustment.

The common gear backlash issue was handled by using small gear pitch of 0.4 module (module was calculated by the gear diameter divided by number of teeth). The high inertia of the stepper motor also helped holding the position of the gear to minimize the backlash problem. These contributed to the accuracy of lens positioning.

3.1.4.3 Electronic Support

3.1.4.3.1 Hardware

The major hardware required was a microcontroller unit (MCU), a stepper motor driver circuit and a user control circuit. An 89C58 microcontroller unit (MCU) was used to control the turning of the stepper motor. The MCU stored an Assembly program which was customized for this micro-display system. Through the program, the MCU sent out signal to the stepper motor driver circuit and the driver circuit sent out signals to the leads of the stepper motor. The stepper motor then turned according to the signals.

The user control board selected the desired position of the lens. There were buttons on the control board and once pressed, a signal would be sent to the MCU and the MCU would control the lens to move to the desired position. The positions could be pre-programmed to different values.

3.1.4.3.2 Software

An Assembly program was written and downloaded to the MCU. Its function was to send suitable signals to the stepper motor driver circuit so as to control the turning of the stepper motor.

3.1.5 Other Prototype Specifications

These specifications were to satisfy other requirements of the experiment. Firstly, the inter-pupillary distance (IPD) for different people was different. The inter-distance between the centre of the left and right lens of the micro-display system (could be referred to as the inter-ocular distance, IOD (Howarth,1999)) was desired to be the same as the IPD so that the viewers could have optimum viewing quality. Therefore the prototype system needed to have its IOD adjustable to suit different viewers.

In the experiment, it was necessary to fix the head position of the participants. The system would provide a forehead and chin rest to cater to this need.

3.2 Assembly and Testing of the Prototype System

3.2.1 Assembled System

Several pictures of the assembled prototype system with adjustable lens focus are presented.

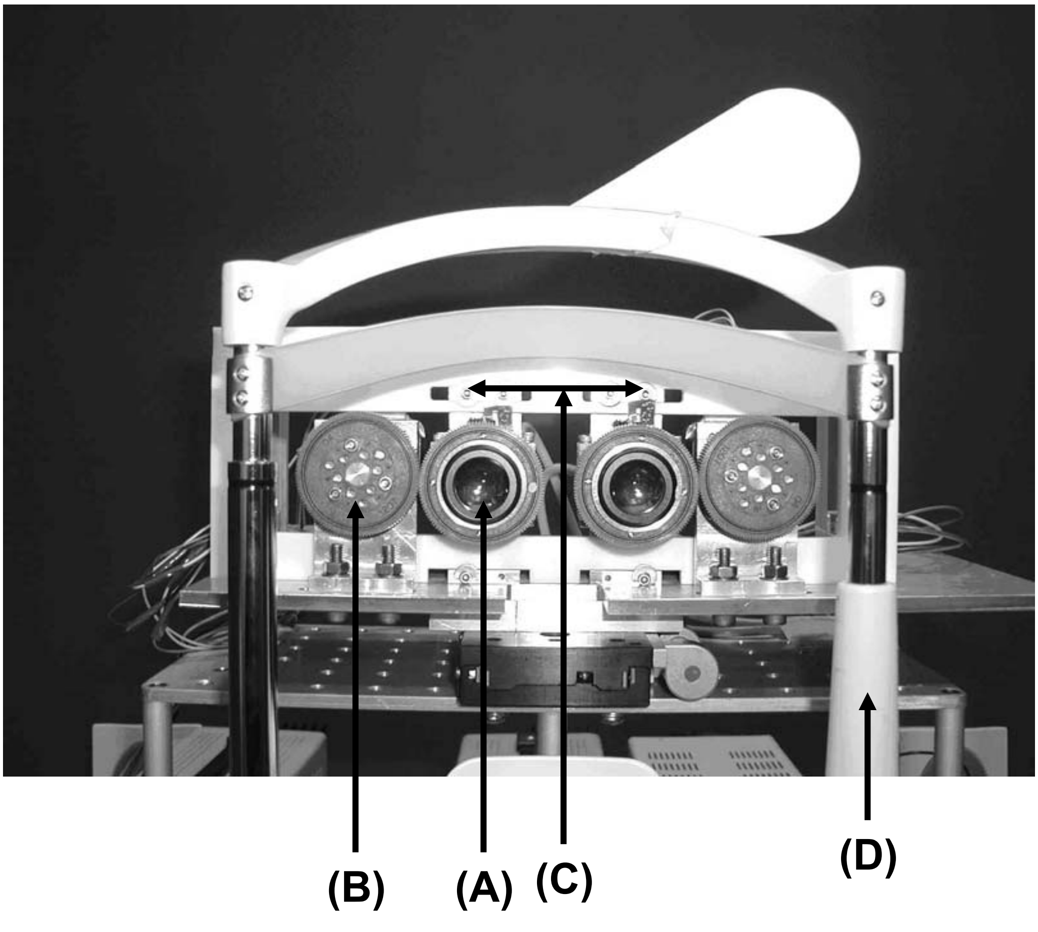

Fig 3.3. A photo showing the prototype binocular micro-display system with dynamically adjustable lens focus.

Fig 3.3 shows the front view of the assembled system. (A) is the magnifying lens of the micro-display system. Viewers watch the micro-display through the lens. (B) shows the gear arrangements. The gear pointed by (B) is mounted with the stepper motor. The gear motor engages with the lens gear. At (C), the inter-distance between the centre of the left and right micro-display system (IOD) can be adjusted. (D) is the forehead and chin rest.

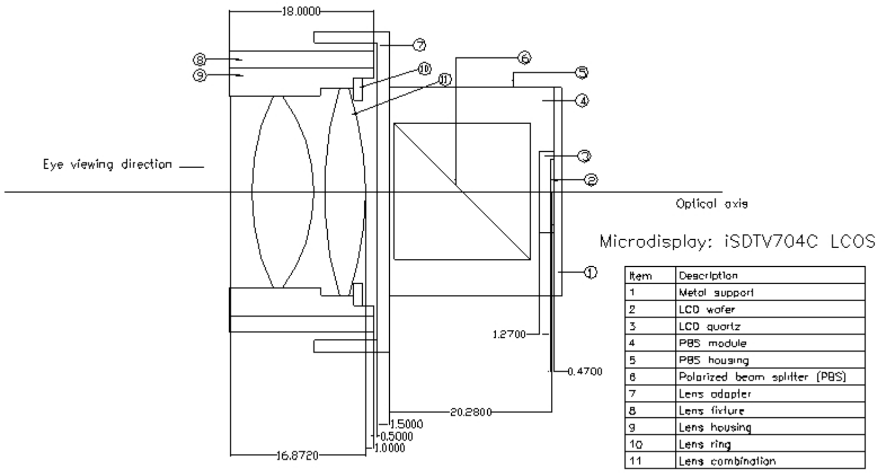

Fig 3.4. A sectional drawing showing the internal structure of the prototype micro-display system. The custom-built lens adapter assembled onto the retrofit iSDTV704C micro-display system. Not all components are drawn e.g. the gear arrangement and the threads on the lens fixture and lens adapter.

Fig 3.4 is a sectional drawing illustrating the internal structure of the prototype system. The right part of the assembly is the iMD iSDTV704C micro-display unit. It has been retrofit so that the left part of the assembly, the dynamically adjustable lens focus module can be assembled onto it. The lens is held by the lens fixture. When the lens fixture screws in and out dynamically by the stepper motor via the gear arrangements, the inter-distance between the lens and the micro-display screen changes, and so the lens focus could be adjusted dynamically.

The last figure demonstrates the scenario when a viewer uses the prototype system. The viewer should be seated and place his / her head at the forehead and chin rest.

The prototype system provides sufficient eye relief so viewers wearing corrective spectacles can also use the system.

Fig 3.5. A photo showing a viewer (face shaded) located his head at the forehead and chin rest and viewing at the micro-display.

3.2.2 Testing and Commissioning

In the commissioning stage, the stepper motor drove the lens to different positions and then the displacement of the lens was measured so as to see whether the lens moved to the desired position accurately.

The lens was moved to different positions and testing was conducted to verify whether the actual lens focus was the same as the calculated lens focus determined by that lens position. The test was to use a manual focus camera to capture the micro-display image through the lens. To capture a sharp micro-display image, the camera focus had to be adjusted to the level that was same as the actual lens focus. Then the actual lens focus could be compared with the calculated lens focus. Though this test did not provide a precise value of the actual lens focus, from the observation of the lens focus values results obtained in the test, it was consistent with the calculated lens focus.

The testing and commissioning process verified that the dynamically adjustable lens focus module functioned.

4 Introduction to the Experiment

4.1 Overview

4.1.1 Introduction

In Chapter 2, the research gaps are presented. Firstly, the micro-display viewer can have difficulty in forming a single stereoscopic image when the lens focus of the micro-display system does not match with the stereoscopic depth cues. The reason for the difficulty could be due to the conflict between accommodation and vergence at the viewers' ocular system. Currently, this difficulty has not been evaluated and studied. Secondly, further to the theory of the conflict between accommodation and vergence, it is hypothesized that if the lens focus matches with the stereoscopic depth cues, there would be no conflict between accommodation and vergence, and that the viewer can form a single stereoscopic image faster. A review of literature indicates that this hypothesis has not been verified. Furthermore, the time taken to form a single stereoscopic image presented on a micro-display has not been studied.

An experiment, approved by the Human Subject Experiment Committee at the Hong Kong University of Science and Technology, was conducted to fill the research gaps. The objectives are to study the effects of matching lens focus with stereoscopic depth cues on the time taken for viewers to form a single stereoscopic image presented on a micro-display at two scenarios (1) lens focus matches with, i.e. is equaled to, stereoscopic depth cues, and (2) lens focus not matching with, i.e. is not equaled to, stereoscopic depth cues.

In the following sections in Chapter 4, the detailed objectives, design of experiment, selection of variables are discussed. The results of this experiment are presented in Chapter 5.

4.1.2 The Use of the Term "Single Image Formation Time" and "Object Depth"

From here onwards, the time taken for viewers to form a single stereoscopic image will be referred to as "single image formation time". The definition and methodology to measure the single image formation time will be described in Section 4.3.2.

In addition, the term stereoscopic depth cues will be referred to as "object depth" in the rest of the thesis.

4.2 Objectives

The main objective of the experiment is to study the effect of matching lens focus with object depth on the single image formation time. To fulfill this objective, appropriate levels of lens focus and object depth have been selected and the selection will be described in the subsequent sections. The inter-participant differences will also be investigated.

4.3 Independent, Dependent and Controlled Variables

4.3.1 Independent Variables

There were two independent variables in the experiment: lens focus and object depth.

Two levels of lens focus (40c, and 200cm) and two levels of object depth (40cm and 200cm) were used. This formed a full factorial of four conditions:

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

Placing images at a depth of 40cm and 200cm will cover near-viewing condition (40cm) and the far-viewing condition (200cm) (Shibata et al, 2004). A depth of infinity was not used because the size of the image will be zero. In addition, a lens focus of 200cm has been used by a current micro-display manufacturer (iMD Micro-display Ltd) as the fixed lens focus value for their display products.

4.3.2 Dependent Variables

The dependent variable in this study was the single image formation time. The participants were asked to indicate whether they saw a single or double image through a computerized response system. The maximum duration for the participants to form a single stereoscopic image was 30 seconds. From a pilot trial conducted before this experiment, it was found that most viewers could complete the formation of a single stereoscopic image within 30 seconds. If there was a case where the participant could not form a single stereoscopic image within 30 seconds, for analysis purposes, the single image formation time would be treated as 30 seconds. The treatment could be referred to Webb and Griffin (2002). During the 1200 data runs among the 10 participants in the study, only 3 runs had recorded a single image formation time of 30 seconds or more.

4.3.3 Controlled Variables

The controlled variables were mainly related to the environment, the apparatus, and the instructions given to the participants.

4.3.3.1 Environment

The experiment was conducted in an indoor air-conditioned laboratory. During the experiment task, only the micro-display was turned on and was the only light source to the participant. During the resting period, the laboratory was in complete darkness. The complete darkness environment allowed the participants to adjust their accommodation to their state of dark focus.

4.3.3.2 Apparatus

The binocular micro-display used in the experiment had a resolution of 688 (horizontal) * 480 (vertical). It was manufactured by iMD Micro-display Ltd, Hong Kong, PRC. The colour of the display was RGB 24-bit. The diagonal field of view was 30 degree for each eye.

4.3.3.3 Instructions to the Participants

The participants were asked not to rub their eyes during the experiment. They were allowed to blink, but they were asked to keep the duration of eye closing to less than 1 second. The participants were not allowed to rest by closing their eyes or taking a short nap. Participants who were suffering from any form of illness were asked to come back on another day. This, fortunately, did not happen in this study.

4.4 Design of the Experiment

The experiment was separated into two **sessions** and used 10 participants. All participants took part in all four **conditions** that were the full factorial combinations of the two levels of lens focuses and two levels of object depths. After each condition, the participants were asked to rest in complete darkness for five minutes. In each condition, the participants were asked to view a binocular display and form a single stereoscopic image five times. Each stereoscope single image formation was called one **dependent repetition**. The presentation order of the four conditions was randomized and was different among participants. After the presentation of the four conditions (each with five dependent repetitions), the whole procedure was repeated two more times (**i.e., three repeated blocks (rep_block)**). For each participant, the order of presenting the four conditions in each repeated block was the same. In summary, each participant performed three repeated blocks of four conditions with five dependent repetitions in one session.

All participants were asked to come back for a second session after 3 days. The second session had the same experiment sequence as the first session. The presentation sequence of the four conditions for each participant was the same as that of the first session. The separation of three days or more was to reduce any accumulative effect of eye fatigue.

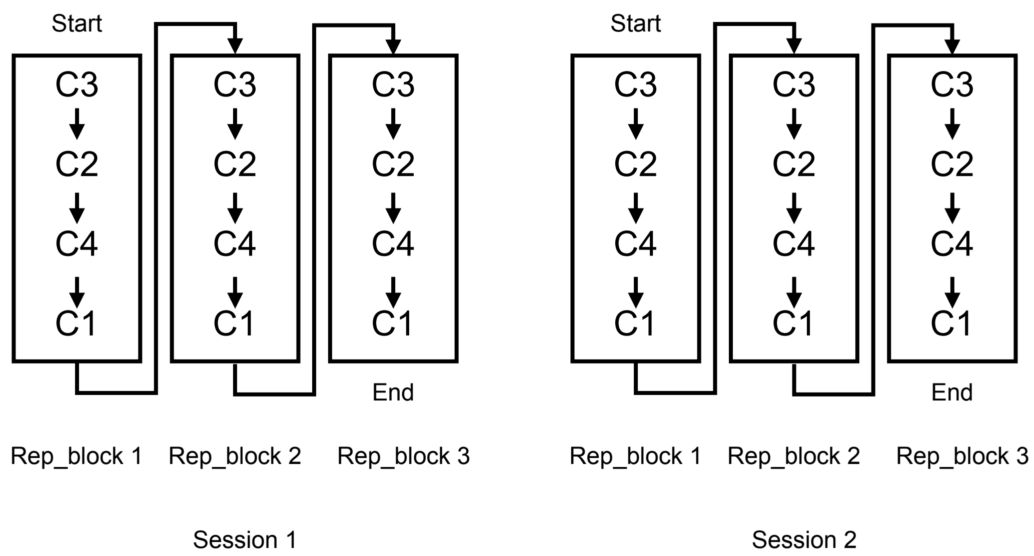

Fig 4.1 A figure showing an example of the experiment sequence. The presentation order of the four conditions C1, 2, 3 and 4 is the same in Rep_block 1, 2 and 3. Session 2 have the same experiment sequence as Session 1.

In the study, every participant had to perform tasks of forming a single stereoscopic image 120 times, which was the exhaustive combination of 5 dependent repetitions (in each condition) * 4 conditions (in each Rep_block) * 3 Rep_block * 2 Sessions.

The five dependent repetitions were averaged and formed a better mean estimation. Therefore, the data size in the data analysis was 240 (i.e. 1 mean data in each condition * 4 conditions * 3 Rep_block * 2 sessions * 10 participants).

4.5 Experiment Task and Image Content

4.5.1 Image Content

During the experiment, participants viewed stereoscopic images of a static virtual environment containing a room and two objects. The two objects were two 3-D texts showing the characters: "DIST40" and "DIST200". The object "DIST40" was placed at a virtual depth of 40cm whilst the object "DIST200" was placed at a virtual depth of 200cm. The room had a virtual depth of 20m. Figure 4.2 illustrates a snap-shot of the virtual room with the two objects.

Fig 4.2. A pair of binocular images of the experiment task. The left and right image represent the image displayed on the left and the right-side of the micro-display respectively.

4.5.2 Experiment Task and Procedure within One Task

As explained earlier, each participant would complete in total 120 tasks of forming a single stereoscopic image. The task was designed to measure the single image formation time. Before each task, the participants were informed to fixate on either the "DIST40" or "DIST200" depending on the particular condition and they were asked to fixate at that object at all time during the task. Also, the lens focus was preset to the appropriate level corresponding to that condition.

At the beginning, biocular (identical) images were presented to the participants and they would form a single biocular image without converging their eyes. This image was not a single stereoscopic image because the images were biocular instead of binocular. Figure 4.3 illustrates the biocular view of the virtual room with the two 3D text objects.

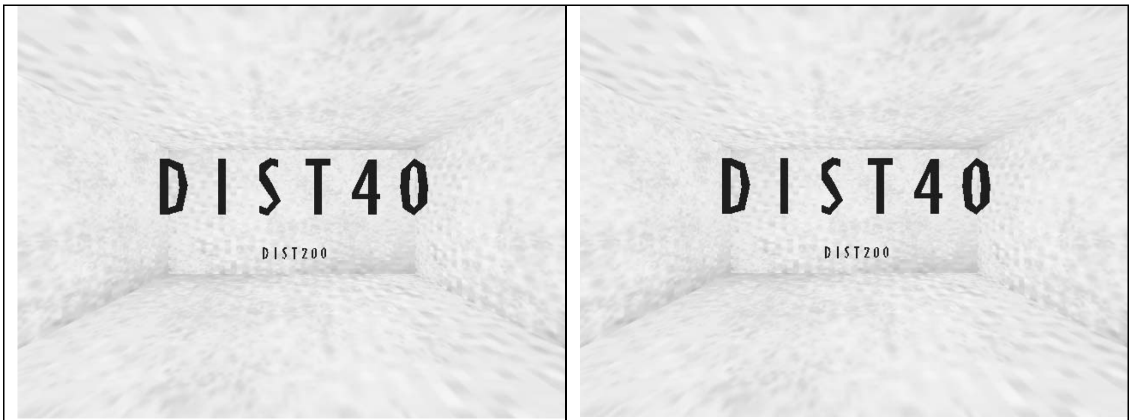

Fig 4.3. A pair of biocular (identical) images of the experiment task. The left and right image represent the image projected from the left and right micro-displays respectively.

After the participants indicated that they had formed a single image for about ten seconds, binocular images were presented to the participants after a further delay of randomly varied period ranged from 3 seconds to 20 seconds. The random delay was designed to avoid habituation responses. The participants were expected to perceive double images instantly and would need to verge their eyes so as to form a single stereoscopic image. Participants were instructed to indicate whether they saw a single image or double images using a response button. If they saw double images, they had to press the button and when they saw a single image, they had to release the button. The time difference between the first instance of the presentation of the binocular images and the first instance the participants released the response button was the single image formation time.

After the participants had formed a stereoscopic single image for about ten seconds, the binocular images were reset back to the biocular images after another random delay (between 3 seconds to 20 seconds) for the beginning of the next task.

4.5.3 The Construction of the Virtual Environment

The virtual environment content was rendered by the virtual environment authoring and rendering software WorldToolKit^{TM}. It was used to generate a synchronized stereoscopic VR simulation. The WorldToolKit^{TM} ran on an SGI Infinity-Reality workstation and output the VR simulation in two synchronized stereoscopic VGA streams. One stream was for the left display and the other stream was for the right display.

4.5.4 Capturing of the Task Content Output

The stereoscopic binocular views were generated for a range of inter-pupillary distances (IPDs) so that the correct stereoscopic views could be presented to the participants according to their IPDs. Images were exported in the form of uncompressed bitmap format in a resolution of 640*480 and presented to the left and the right micro-display LCD panels using a Pentium 4 PC.

4.6 Ocular Processes Involved in the Four Conditions in the Experimental Task

In this study, participants needed to converge (turn the eyes inward) and / or diverge (turn the eye outward) their eyes in order to form a single stereoscopic image. This section presents the theoretical ocular processes expected during each of the four conditions.

4.6.1 Condition 1 (Lens focus: 40cm; Object depth: 40cm)

The participants were informed to fixate on the 3-D text object "DIST40" while the eyes were required to accommodate to a lens focus of 40cm.

- At the beginning, biocular images were presented:

  The participants looked straight and the left and right line-of-sights were parallel. In other words, the participants verged at infinity. To achieve this, the participants needed to use negative fusional convergence.

- Then binocular images were presented:

  The participants converged to 40cm. No fusional convergence was used at this at stage.

- Finally, biocular images were presented again:

  The participants needed to diverge at infinity. Negative fusional convergence was again used.

4.6.2 Condition 2 (Lens focus: 200cm; Object depth: 40cm)

The participants were informed to fixate at the 3-D text object "DIST40" while the eyes were required to accommodate to a lens focus of 200cm.

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- At the beginning, biocular images were presented:

  The participants verged at infinity. Negative fusional convergence was used.

- Then binocular images were presented:

  The participants converged to 40cm. Positive fusional convergence was used because the participants' natural convergence responses were to 200cm.

- Finally, biocular images were presented again:

The participants diverged at infinity. Negative fusional convergence was again used.

4.6.3 Condition 3 (Lens focus: 40cm; Object depth: 200cm)

The participants were informed to fixate at the 3-D text object "DIST200" while the eyes were required to accommodate to a lens focus of 40cm.

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- At the beginning, biocular images were presented:

  The participants verged at infinity. Negative fusional convergence was used.

- Then binocular images were presented:

  The participants converged to 200cm. Negative fusional convergence was used because the participants were expected to verged naturally at 40cm.

- Finally, biocular images were presented again:

  The participants diverged at infinity. Negative fusional convergence was again used.

4.6.4 Condition 4 (Lens focus: 200cm; Object depth: 200cm)

The participants were informed to fixate and form single image at the 3-D text object "DIST200" while the eyes were required to accommodate to a lens focus of 200cm.

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- At the beginning, biocular images were presented:

  The participants verged at infinity. Negative fusional convergence was used.

- Then binocular images were presented:

  The participants converged to 200cm. No fusional convergence was used.

- Finally, biocular images were presented again:

The participants diverged at infinity. Negative fusional convergence was used.

4.7 Hypothesis

It was hypothesized that the participants would take significantly shorter time to form a single stereoscopic image when the lens focus was equaled to (i.e. matched with) the object depth. When the lens focus matched with the object depth, the participants did not need to use extra positive or negative fusional convergence ability to overcome the conflict between accommodation and vergence. Consequently, the participants could form a single stereoscopic image in a shorter time.

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

H1: at lens focus 40cm, the single image formation time at object depth 40cm (a matched condition) was significantly shorter than that of at object depth 200cm (an unmatched condition).

H2: at lens focus 200cm, the single image formation time at object depth 200cm (a matched condition) was significantly shorter than that of at object depth 40cm (an unmatched condition)

H3: at object depth 40cm, the single image formation time at lens focus 40cm (a matched condition) was significantly shorter than that of at lens focus 200cm (an unmatched condition)

H4: at object depth 200cm, the single image formation time at lens focus 200cm (a matched condition) was significantly shorter than that of at lens focus 40cm (an unmatched condition)

4.8 Apparatus and Procedure

The prototyped micro-display system with dynamically adjustable lens focus presented in Chapter 3 was used in the experiment. The system supported individualized inter-pupillary distance (IPD) adjustment. The diagonal display area was 0.56”, the diagonal field-of-view was 30^{o} and the resolution was 688 (Horizontal) * 480 (Vertical). Since the resolution of the images was 640*480, when the images were transmitted to the video driver of the micro-display, the horizontal resolution of the image signal was scaled up from 640 pixels to 688 pixels and could fill the whole panel area.

The procedure of the experiment is presented in the Appendix.

4.9 Participants

4.9.1 Preferences

There was no special preference on the gender of the participants. Young adults were preferred and the age of the participants would be kept between 18 to 30.

4.9.2 Criteria

Several screening criteria concerning the visual parameters of the participants were imposed. The reasons were to ensure that the participants could have sufficient visual ability to see the image sharply, to fuse the binocular images into one single stereoscopic image, and had no serious binocularity problem which avoided them to perform the experiment task.

To qualify for the experiment, participants had to attain visual acuity equaled or more than 20/20 in both near (14 inch, i.e. 36cm) and distance (20 feet, i.e. 6.1 meter) tests, no colour blindness and normal stereopsis (test result 40 seconds of arc or less).

Vision screening tests were conducted before the experiment. The vision test OPTEC 2000 from Stereo Optical Co., Inc was used. Only participants who passed the vision screening test were qualified for the experiment.

5 Results, Findings and Discussion

5.1 Overview

The main dependent variable measured was the single image formation time. As mentioned in Chapter 4, each participant had to complete 120 single stereoscopic image formation tasks which represented the exhaustive combination of 5 dependent repetitions (within each condition), 4 conditions, 3 repeated blocks (rep_blocks), and 2 sessions. There were 10 participants in total and the total number of data points was 1200 (10 participants * 120 data per participant).

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

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

The statistical software SAS (The SAS System for Windows, Release 8.02) was used in the parametric analysis. In supplement, another statistical software Minitab (Minitab Release 14) was employed in the data transformation for the parametric analysis. Besides SAS, the statistical software SPSS (SPSS 13.0 for Windows) was also used in the non-parametric analysis.

5.2 Participants

There were 10 participants in the experiment. They were volunteers and consented to participate in the experiment. Before the experiment, they signed a consent form to indicate their consent. All of the participants passed the vision screening test. The experiment has been approved by the Human Subject Experiment Committee at the Hong Kong University of Science and Technology.

There were six males and four females. The age of ten participants ranged from 20 to 29. The mean age was 23 years old. The standard deviation was 3.09 years.

5.3 Fundamental Analyses: ANOVAs, SNK Tests, and Supportive Non-parametric Methods

5.3.1 Normality Test

The assumptions of ANOVA are normality, constant variance and independence of the data. As such the normality of the data set (with 240 data points) is examined using normality plots and Shapiro-Wilk test. The Shapiro-Wilk test is suitable for data size from 3 to 2000. The Shapiro-Wilk Statistic W ranges from 0 to 1. If W is close to 1, the data can be considered as normal. The p-value smaller than 0.05 leads to the rejection to the null hypothesis that the data is normally distributed.

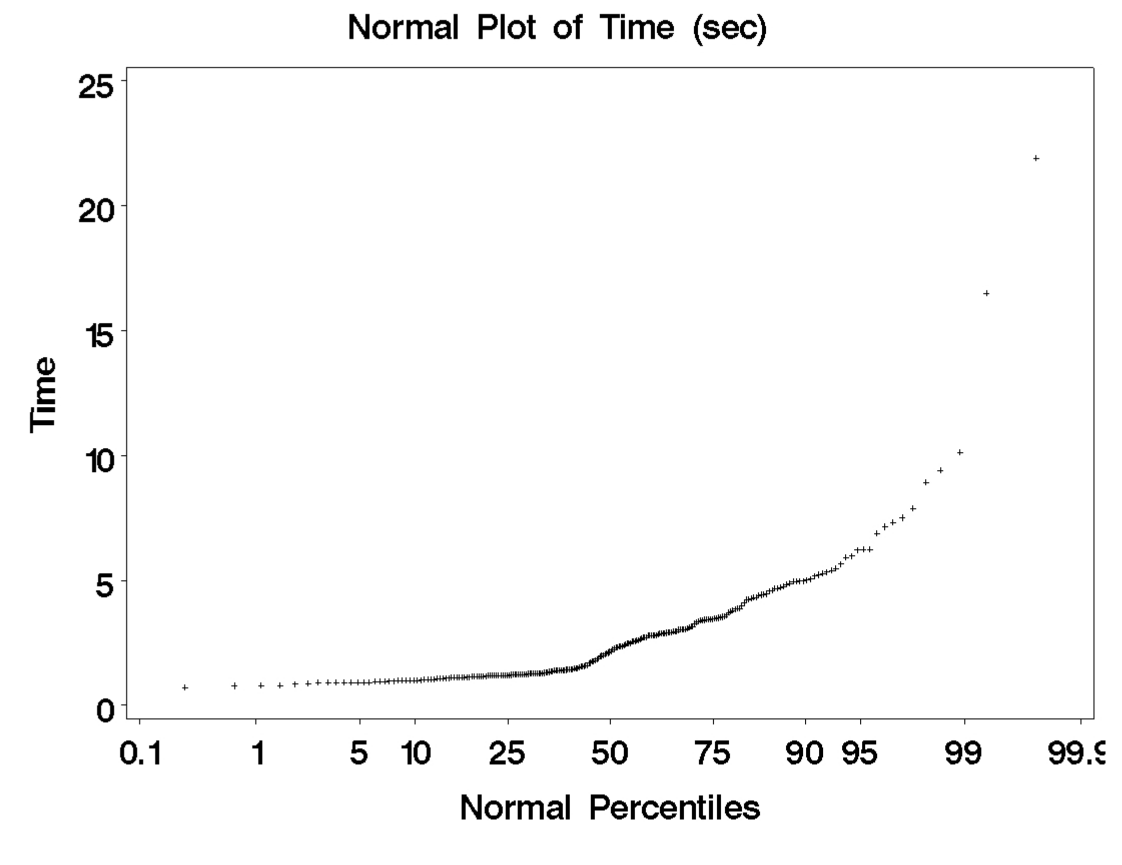

Fig 5.1. Normality plot of the 240 time data taken to form a single stereoscopic image of a virtual object.

Inspections of Figure 5.1 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 was 0.6849 ($p<0.0001$). Consequently, the data should be transformed so as to improve its normality.

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

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

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

Minitab was used to recommend the lambda value (λ). The confidence level was 95.0%. The suggested best value of λ by Minitab for the 240 data was -0.5.

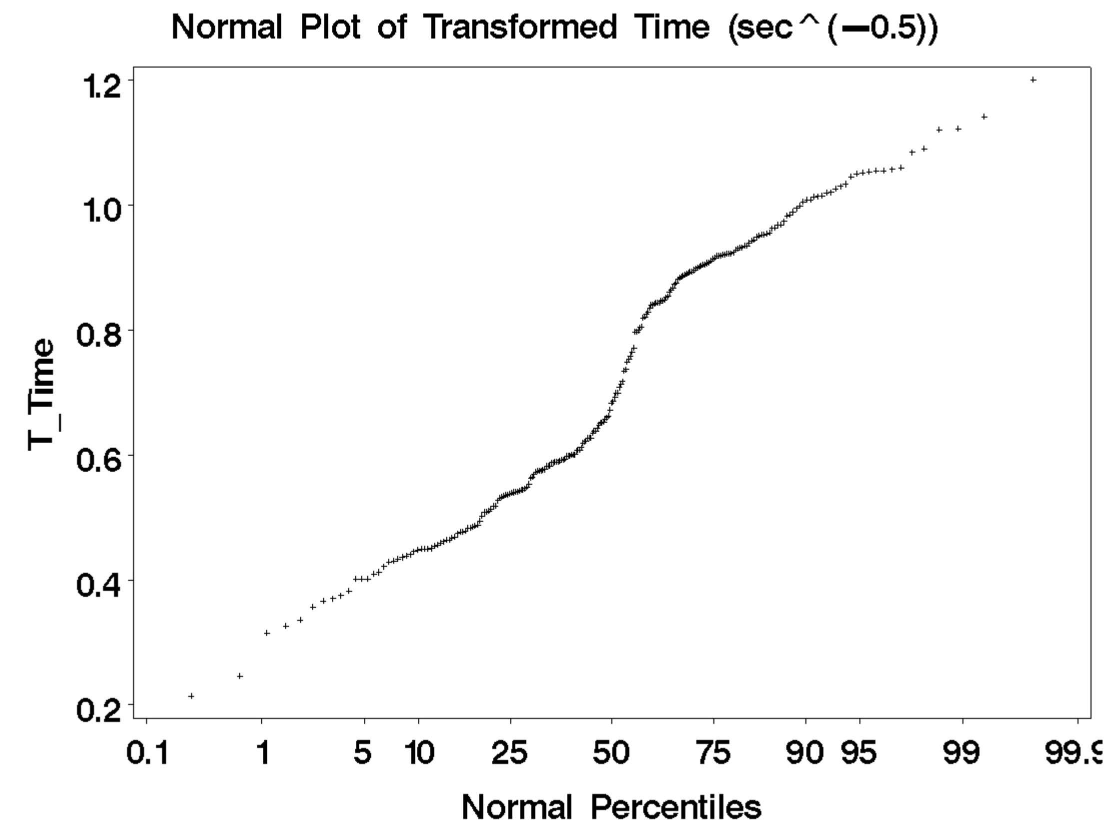

Fig 5.2. Normality plot of the 240 Box-Cox transformed (λ =-0.5) time data taken to form a single stereoscopic image of a virtual object.

The above normality plot of the 240 transformed data showed that the normality of the data was more satisfactory than that of before transformation. In the Shapiro-Wilk test, the W value was 0.9542 but the p value was smaller than 0.0001. The Shapiro-Wilk test did not support the transformed data was normal.

Since after data transformation the data still could not satisfy the assumptions of ANOVA, all the significant results obtained by ANOVA were verified by non-parametric tests.

5.3.2 ANOVA

In the ANOVA, the main effects of lens focus, object depth, repeated block (rep_block), session and gender, and their two-way interactions were studied. Interaction means that the effect of one independent variable on a dependent variable is not equal for all levels of the other independent variable (Stevens, 2002). The effects of matching lens focus with object depth could be observed by the interaction effects between lens focus and object depth.

The ANOVA Procedure

Dependent Variable: T_Time (Time was Box-Cox transformed, lambda=-0.5)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	20	2.60841909	0.13042095	3.26	<.0001
Error	219	8.76426888	0.04001949		
Corrected Total	239	11.37268797			

Source	DF	Anova SS	Mean Square	F Value	Pr > F
LensFocus	1	0.08852999	0.08852999	2.21	0.1384
ObjectDepth	1	0.13159150	0.13159150	3.29	0.0711
Session	1	0.73373664	0.73373664	18.33	<.0001
Rep_Block	2	0.02816947	0.01408473	0.35	0.7037
Gender	1	0.95783467	0.95783467	23.93	<.0001
LensFocus*ObjectDepth	1	0.48933894	0.48933894	12.23	0.0006
LensFocus*Rep_Block	2	0.00272389	0.00136195	0.03	0.9665
ObjectDept*Rep_Block	2	0.02419027	0.01209514	0.30	0.7395
LensFocus*Session	1	0.00357687	0.00357687	0.09	0.7653
ObjectDepth*Session	1	0.00845796	0.00845796	0.21	0.6462
Rep_Block*Session	2	0.02120600	0.01060300	0.26	0.7675
Gender*LensFocus	1	0.06707693	0.06707693	1.68	0.1968
Gender*ObjectDepth	1	0.01452479	0.01452479	0.36	0.5475
Gender*Rep_Block	2	0.02622742	0.01311371	0.33	0.7209
Gender*Session	1	0.01123374	0.01123374	0.28	0.5968

Table 5.1. The Analysis of Variance (ANOVA) Table for the time (Box-Cox transformed, λ =-0.5) taken to from a single stereoscopic image of a virtual object. Studies of the factors of object depth (40cm and 200cm), lens focus (40cm and 200cm), rep_block (1 to 3), session (1 to 2) and gender (male and female). Data of 10 participants.

5.3.2.1 Main Effects

From the ANOVA table, the only significant main effect was session ($p<0.0001$) and gender ($p<0.0001$). The main effects of lens focus, object depth and rep_block were not significant.

5.3.2.2 SNK Tests on the Significant Main effect

To further understand the nature of the significant main effect of session and gender, Student-Newman-Keuls (SNK) test was applied to determine how the levels of the main effects affect the single image formation time. Box-Cox transformed single image formation time was used in the SNK test. Since the lambda value used in the transformation was -0.5, the larger the value of the transformed data, the smaller the value of the original data. Simply speaking, the larger the transformed value, the shorter the single image formation time. In the SNK test, the alpha used was 0.5.

The SNK test results showed that for session, the single image formation time at Session 2 was significantly shorter than that of at Session 1 (Table 5.2a). For gender, the single image formation time at female was significantly shorter that of at male (Table 5.2b).

Student-Newman-Keuls Test for Time

Alpha	0.05
Error Degrees of Freedom	234
Error Mean Square	0.044405

Number of Means	2
Critical Range	0.0535967

Means with the same letter are not significantly different.

SNK Grouping	Mean	N	Session
A	0.77227	120	2
B	0.66169	120	1

Table 5.2a. SNK test result on the main effects of session to the transformed single image formation times of ten participants. Means with the same letter are not significantly different. The mean value is the Box-Cox transformed single image formation time (unit: $sec^{-1/2}$).

Student-Newman-Keuls Test for T_Time

Alpha	0.05
Error Degrees of Freedom	219
Error Mean Square	0.040019
Harmonic Mean of Cell Sizes	115.2

NOTE: Cell sizes are not equal.

Number of Means	2
Critical Range	0.0519493

Means with the same letter are not significantly different.

SNK Grouping	Mean	N	Gender
A	0.79435	96	Female
B	0.66540	144	Male

Table 5.2b. SNK test result on the main effects of gender to the transformed single image formation times of ten participants. Means with the same letter are not significantly different. The mean value is the Box-Cox transformed single image formation time (unit: $sec^{-1/2}$).

To confirm the ANOVA result, Kruskal-Wallis test was conducted in SAS to study the main effects. The test result confirmed that session and gender were significant effects ($p<0.0001$).

5.3.2.3 Two-way Interaction Effects

The only significant two-way interaction effect was the interaction between lens focus and object depth ($p=0.001$). This indicated that matching and unmatching lens focus with object depth could have a significant influence on the data.

5.3.3 Observations at Interaction Plot and SNK Test

5.3.3.1 Interaction Plot between Lens Focus and Object Depth

The most concerned interaction effect was the interaction between lens focus and object depth, which represented the effect of matching lens focus with object depth. On the interaction plot, three were three observations on the single image formation time at different matched and unmatched cases.

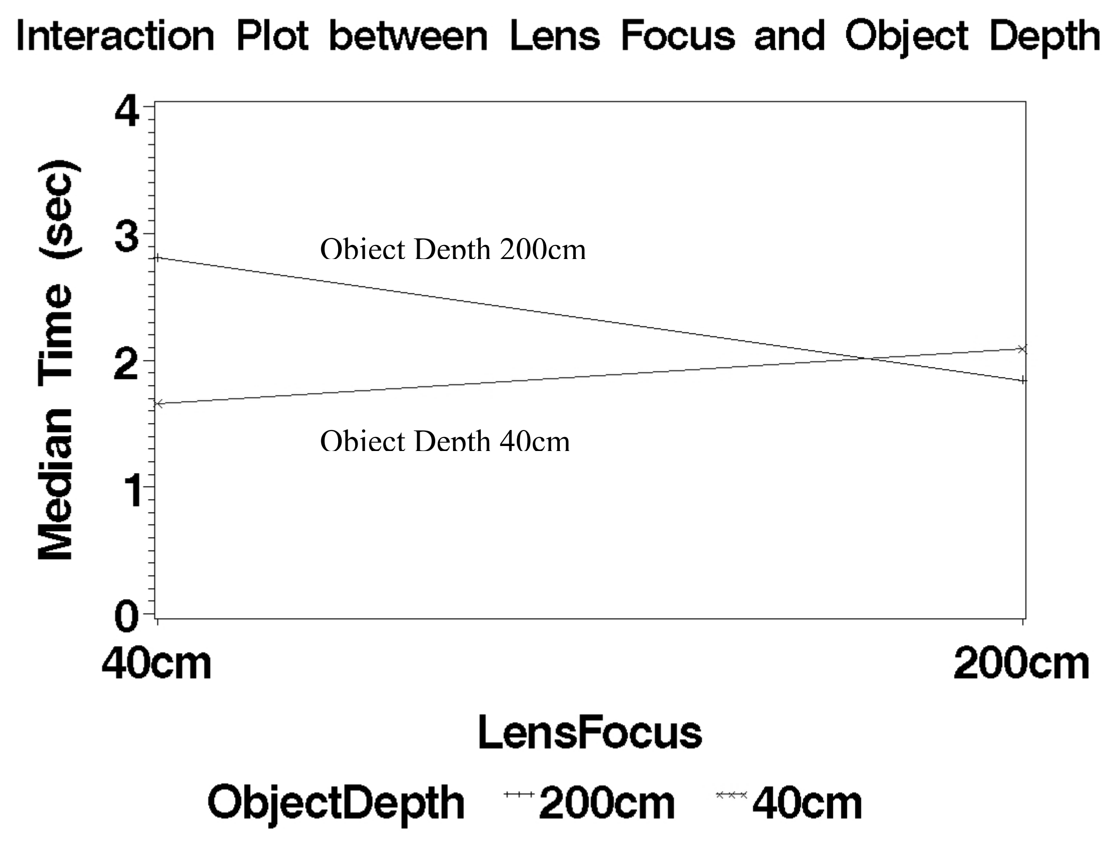

Fig 5.3. An interaction plot between the main effects of lens focus (40cm and 200cm) and object depth (40cm and 200cm) on the median single image formation time for 10 participants.

Firstly, when the lens focus matched with the object depth (matched conditions), the median single image formation time was shorter than that of when the lens focus did not match with the object depth (unmatched conditions). It could be seen that when the object depth was 40cm, the median single image formation time at lens focus 40cm (1.66sec) (matched condition) was shorter than at lens focus 200cm (2.09sec) (unmatched condition). When object depth was 200cm, the median single image formation time at lens focus 200cm (1.84sec) (matched condition) was shorter than at lens focus 40cm (2.81sec) (unmatched condition). This indicated that if the lens focus matched with the object depth, the single image formation time would be shorter.

Secondly, it could be observed that the effect of matching could be varied at different levels of lens focus and object depths. When lens focus was 40cm, the median single image formation time at object depth 200cm and 40cm appeared to have a large difference. However, when lens focus was 200cm, the median single image formation time at object depth 200cm and 40cm appeared to have only a small difference. In other words, the effect of matching at lens focus 40cm was more obvious than at lens focus 200cm.

Thirdly, it was felt there would be interest in the single image formation time among different levels of matched conditions and different levels of unmatched conditions. For the matched conditions, the median single image formation time at lens focus 40cm, object depth 40cm was slightly smaller than that of at lens focus 200cm, object depth 200cm. For the unmatched conditions, the median single image formation time at lens focus 200cm, object depth 40cm was more observably smaller than that of at lens focus 40cm, object depth 200cm. It could be observed from the plot that generally the single image formation times were shorter at object depth 40cm. This observation did not mean that object depth 40cm would lead to shorter single image formation time since it involved the strong interaction effect between lens focus and object depth. This observation reflected the nature of the interaction between lens focus and object depth at different combinations, and would be further studied by statistical methods in the subsequent section.

5.3.3.2 SNK Test on the Interaction between Lens Focus and Object Depth

To understand more about the four matched and unmatched conditions, ANOVA and SNK test were performed again with the factor condition added into the model. The designations, mentioned in Chapter 4, were recapped here:

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

Student-Newman-Keuls Test for T_Time

Alpha	0.05
Error Degrees of Freedom	236
Error Mean Square	0.045183

Number of Means	2	3	4
Critical Range	0.0764555	0.0915362	0.1004153

Means with the same letter are not significantly different.

SNK Grouping	Mean	N	Condition
A	0.76634	60	1
A	0.75792	60	4
A	0.71445	60	2
B	0.62920	60	3

Table 5.3. SNK test result on the main effects of condition to the transformed single image formation times of ten participants. Means with the same letter are not significantly different. The mean value is the Box-Cox transformed single image formation time (unit: $sec^{-1/2}$).

The single image formation time at the two matched conditions (Condition 1 and 4) appeared to be shorter than the two unmatched conditions (Condition 2 and 3). The SNK test found that the single image formation time at Condition 3 was significantly longer than at Condition 1, 2 and 4. It found no significant difference between single image formation times at Condition 1, 2 and 4.

Results from ANOVA indicated that the main effect of condition was significant (p=0.0016). Kruskal-Wallis test was conducted in SAS to study the effect of condition. The test result confirmed that condition was a significant effect (p=0.0017).

Referring to the second finding in the previous section, the SNK finding confirmed that the effect of matching at lens focus 40cm was more obvious than at lens focus 200cm. To describe this in more detail, it could be seen that when the lens focus was 40cm, the mean single image formation time at object depth 40cm (matched condition, Condition 1) was significantly smaller than at object depth 200cm (unmatched condition, Condition 3). However, when the lens focus was 200cm, the mean single image formation time at object depth 200cm (matched condition, Condition 4) was not significantly shorter than at object depth 40cm (unmatched condition, Condition 2).

The description above studied the cases of fixing lens focus. In the same way, to study the cases of fixing object depth, it indicated that when object depth was 40cm, the mean single image formation time at lens focus 40cm (matched condition, Condition 1) was not significantly shorter than at lens focus 200cm (unmatched condition, Condition 2). When the object depth was 200cm, the mean single image formation time at lens focus 200cm (matched condition, Condition 4) was significantly shorter than at lens focus 40cm (unmatched condition, Condition 3).

To further study the effect of matching lens focus with object depth in a more in-depth manner, ANOVAs would be conducted on split data sets by fixing lens focus and object depth to 40cm and 200cm in Section 5.4.

5.3.4 Section Summary

Section 5.3 reports the results of parametric analyses on the data. The significant main effects of session and gender and more importantly, the significant 2-way interaction effects between the effects of lens focus and the effects of object depth. Since the assumption of data normality is not valid, further analyses using non-parametric tests are reported in the subsequent sections.

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5.4 Further Analyses on Split Data Sets To Study the Effect of Matching Lens Focus with Object Depth

Following Section 5.3, the effect of matching lens focus with object depth was further studied on split data sets. The 240 data points were classified into four data sets (fixed to lens focus 40cm, lens focus 200cm, object depth 40cm and object depth 200cm). In each data set there was 120 data points. For example, in the data set of lens focus 40cm, it contained 60 data points in which lens focus was 40cm and object depth was 40cm (data in a matched condition) and other 60 data points in which lens focus was also 40cm but object depth was 200cm (data in a unmatched condition).

The methods used were ANOVA, paired t test and Wilcoxon signed rank test. In ANOVA and paired t test, Paired t test was used to cater the participant variation and because paired t test consider the participants variation, its result was more realistic than the ANOVA result when compared with the Wilcoxon signed rank test result. Box-Cox transformation was employed at ANOVA and paired t test in which lambda value -0.5 was used. In the four data sets, the distribution of the Box-Cox transformed data was still not normal ($p<0.05$, Shapiro-Wilk test). The effect of matching lens focus with stereoscopic depth cues in each data set would be studied.

5.4.1 Findings

When lens focus was fixed at 40cm (i.e. data at Condition 1, a matched condition; and Condition 3, an unmatched condition), the effect of matching (i.e. the effect of object depth) was significant ($p=0.0005$, ANOVA). Paired t test indicated that the effect of matching was significant ($p=0.0002$). Wilcoxon signed ranks test run by SPSS confirmed the significant effect of matching ($p=0.000$). In other words, hypothesis H1 (see Chapter 4) is supported.

When lens focus was fixed at 200cm (i.e. data at Condition 4, a matched condition; and Condition 2, an unmatched condition), the effect of matching was not significant ($p=0.2325$). On the contrary, paired t test indicated that the effect of matching was significant ($p=0.0002$). Wilcoxon signed ranks test found that the effect of matching was not significant ($p=0.092$). In other words, both the results of ANOVAs and non-parametric tests reject hypothesis H2 (see Chapter 4) but the results of paired t test support H2. Since the data are not normally distributed, the author treats the results of non-parametric tests as more reliable and therefore H2 is rejected.

When object depth was fixed at 40cm (i.e. data at Condition 1, a matched condition; and Condition 2, an unmatched condition), the effect of matching (i.e. the effect of lens focus) was significant (p=0.1464). However, paired t test indicated that the effect of matching was significant (p=0.0000). Wilcoxon signed ranks test run by SPSS indicated the significant effect of matching (p=0.000). Using the results of non-parametric test, hypothesis H3 is supported.

When object depth was fixed at 200cm (i.e. data at Condition 4, a matched condition; and Condition 3, an unmatched condition), the effect of matching was significant (p=0.0012). Paired t test indicated that the effect of matching was significant (p=0.0000) and Wilcoxon signed ranks test had the same result (p=0.000). Using the results of all three tests, hypothesis H4 is supported.

5.4.2 Discussion on the Findings

It could be seen that among ANOVA, paired t test and Wilcoxon signed ranks test results had different descriptions on the significance of the matching effect. For lens focus fixed at 40cm, object depth fixed at 40cm and object depth fixed at 200cm, the paired t test results and Wilcoxon signed ranks test result were consistent. When lens focus was fixed at 200cm, the paired t test result and Wilcoxon signed ranks test result were not consistent.

Since the normality of the data in each data set was not satisfactory, the Wilcoxon signed ranks test results would be stronger than the paired t test results in describing the significance of the matching effect. ANOVA results served as a reference.

In all of these four data sets, the medium single image formation times of the matched data were shorter than those of the unmatched data. Therefore it could be summarized that Wilcoxon sign ranks test results indicated that for three data set (i.e. lens focus fixed at 40cm; object depth fixed at 40cm; and object depth fixed at 200cm), the single image formation time was significantly shorter when the lens focus matched with the object depth. For the remaining data set (i.e. lens focus fixed at 200cm), the single image formation time was shorter when the lens focus matched with the object depth, but the difference from the time at the unmatched case was not significant.

Back to the four hypotheses listed in Chapter 4, H1, H3 and H4 are supported to be true since for each hypothesis it has been accepted in both paired t test and Wilcoxon signed rank test.

For H2, it is rejected by the Wilcoxon signed ranks test but is accepted only by the results of paired t test. As mentioned earlier, the Wilcoxon signed ranks test result should be more reliable in this case and so H2 is rejected.

Referring to the SNK result in the previous section, it is easy to understand that there had been significant matching effects for lens focus fixed at 40cm and object depth fixed at 200cm, since the single image formation time at Condition 3 was significantly longer than those of at Condition 1 and 4. It is not surprising to learn that there has been no significant matching effect for lens focus fixed at 200cm, since the single image formation time at Condition 2 was not significantly different from those of at Condition 4.

5.4.3 Interactions between the Effect of Matching at Fixed Les Focus / Object Depth and the Effect of Session / Gender

Sessions and genders were significant main effects according to the results of ANOVAs. Hypotheses H1 – H4 were studied at different sessions and genders if there was any change of the significance of the effect of matching at different session and genders. Since the data size was getting small, Wilcoxon signed ranks test was used.

5.4.3.1 Session

H1 is true at both Session 1 ($p=0.000$) and Session 2 ($p=0.007$). The single image formation time at the matched condition are significantly shorter at both Session 1 and Session 2.

H2 is false at both session 1 ($p=0.441$) and session 2 ($p=0.116$). The single image formation time at the unmatched condition have no significant difference from that of at the unmatched condition at both Session 1 and Session 2.

H3 is true at both session 1 ($p=0.002$) and session 2 ($p=0.009$). The single image formation time at the matched condition are significantly shorter at both Session 1 and Session 2.

H4 is true at both session 1 ($p=0.000$) and session 2 ($p=0.000$). The single image formation time at the matched condition are significantly shorter at both Session 1 and Session 2.

5.4.3.2 Gender

H1 is true for both male (p=0.000) and female (p=0.001). The single image formation time at the matched condition are significantly shorter for both male and female.

Interestingly, H2 is true for male (p=0.031) but false for female (p=0.909). The single image formation time at the matched condition are significantly shorter for male but have no significant difference from that of at the unmatched condition for female.

H3 is true for male (p=0.000) but false for female (p=0.710). The single image formation time at the matched condition are significantly shorter for male but have no significant difference from that of at the unmatched condition for female.

H4 is true for both male (p=0.002) and female (p=0.001). The single image formation time at the matched condition are significantly shorter for both male and female.

5.4.4 Section Summary

In Section 5.4 the analyses on split data sets gave a clearer picture on the effects of matching lens focus with object depth. Hypotheses H1, H3, and H4 have been proven to be true and H2 has been rejected. These effects have been shown to be the same across the two sessions and with data from both genders with the exception that H2 and H3 are true for male but false for female.

5.5 Non-parametric Analysis: Wilcoxon Signed Ranks Tests on Split Data Sets To Study the Effect of Matching Lens Focus and Object Depth

In Section 5.3, the transformed data was inspected and found not normally distributed. Therefore it was necessary to use non-parametric tests to confirm the ANOVA results. This has been done in Section 5.4 and in this section, the results of more non-parametric analyses are reported. In addition to the overall main effects of matching lens focus and object depth, the effects of matching in each of the repeated block are also presented.

When the 240 data points were classified into four data sets (lens focus 40cm, lens focus 200cm, object depth 40cm and object depth 200cm), there were 120 data points in each data set. If these 4 groups of data were further split with respect to session (1 and 2) and rep_block (1, 2, and 3), then there would be 24 data sets in which each data set contained 20 data points (10 data points in the matched condition and 10 data points in the unmatched condition). Wilcoxon signed ranks test was used to perform this analysis. The analyzed data was single image formation time.

5.5.1 Findings

The Wilcoxon signed ranks test reported that in each data set, the ranks of the single image formation time at the matched condition shorter than at the unmatched condition were always higher than the ranks of the single image formation time at the unmatched condition shorter than at the matched condition. This meant the occurrence of single image formation time at the matched conditions was shorter than at the unmatched conditions was consistent and did not change in different sessions or rep_blocks.

5.5.1.1 Findings on the Significance Level of the Matching Effect

The summary of the p values of the effect of matching by Wilcoxon signed rank test was presented in the following table.

Lens focus 40cm

p-value of matching effect	Session 1	Session 2
Rep_Block 1	0.086	0.285
Rep_Block 2	0.007	0.005
Rep_Block 3	0.028	0.007

Lens focus 200cm

p-value of matching effect	Session 1	Session 2
Rep_Block 1	0.799	0.646
Rep_Block 2	0.721	0.799
Rep_Block 3	0.241	0.037

Object depth 40cm

p-value of matching effect	Session 1	Session 2
Rep_Block 1	0.139	0.959
Rep_Block 2	0.139	0.093
Rep_Block 3	0.013	0.005

Object depth 200cm

p-value of matching effect	Session 1	Session 2
Rep_Block 1	0.285	0.059
Rep_Block 2	0.047	0.037
Rep_Block 3	0.093	0.007

Table 5.4. The summary of p-values by Wilcoxon signed ranks test of the main effects of matching lens focus with object depth for the time taken to form a single stereoscopic image of a virtual object of 10 participants. Groupings in object depth (40cm and 200cm), lens focus (40cm and 200cm) at 3 repeated blocks (1 to 3) and 2 sessions (1 to 2). P-value of asymptotic Sig. (2-tailed).

With reference to the summary of p-value, there were three major findings. Firstly, the effect of matching was not always significant in the 24 data sets. In all the four major groups of data (lens focus 40cm, lens focus 200cm, object depth 40cm, object depth 200cm), the effect of matching was not significant at Rep_block 1. This happened at both session 1 and 2.

Secondly, generally the p-values decreased along rep_block. Typically speaking, the p-values began to decrease from Rep_block 1 to Rep_block 2 (unless one case at Session 2 when lens focus was fixed at 200cm). In addition, the p-values at Rep_block 3 were always smaller than those at Rep_block. This indicated the effect of matching was more and more significant along rep_block.

Thirdly, the p-values at Session 2 were generally smaller than those at Session 1.

To summarize, it appeared that the effect of matching had a trend of becoming increasingly significant as the experiment progressed. For example, in all the 4 scenarios of fixed lens focus and object depth, the effect of matching was more significant in Rep_block 3 than in Rep_block 1. In addition, the effect of matching was more significant in Session 2, Rep_block 3 than in Session 1, Rep_block 3.

Wilcoxon signed ranks test results in Section 5.4 were recapped. The effect of matching was significant for lens focus fixed at 40cm (p=0.000), object depth fixed at 40cm (p=0.000), and object depth fixed at 200cm (p=0.000). For lens focus fixed at 200cm, the effect of matching was not significant (p=0.092).

It was not surprising to learn that the p-values in the 24 data sets were larger than the p-values obtained at the 4 major groups of data (lens focus 40cm, lens focus 200cm, object depth 40cm and object depth 200cm). The 24 data sets and the 4 major groups of data had a large difference in data size and therefore a large difference in degree of freedom in the analysis.

Though the significant effect of matching did not appear in every data set, in the last rep_block (i.e. Session 2, Rep_block 3) all the 4 data sets had significant effect of matching. This indicated that after runs of single image formation tasks, at the end the participants could benefit from the effect of matching lens focus with object depth.

5.5.1.2 Findings on the Absolute Single Image Formation Time

In the summary of p-values, the significance level of the effect of matching could be observed. The summary of median, first quartile and third quartile in the matched and unmatched condition of each data set was presented in the following table. This summary could show the trend of the absolute single image formation time in different sessions and rep_block.

Lens focus 40cm

Single image formation time (sec)			
		Matched	Unmatched
Session	Rep_Block	25%tile - - Median - - 75%tile	25%tile - - Median - - 75%tile
1	1	1.5534--2.2902--3.5106	1.5146--3.6004--6.0727
	2	1.2245--2.0668--3.2012	2.3894--4.3512--6.6374
	3	1.1025--2.1520--3.4180	1.8613--3.2397--6.1447
2	1	1.0126--1.8527--2.8108	1.2150--1.4734--5.2966
	2	0.9565--1.3471--2.8412	1.2815--2.2011--5.5324
	3	1.0324--1.2387--2.6780	1.2263--2.6145--3.7099

Lens focus 200cm

Single image formation time (sec)			
		Matched	Unmatched
Session	Rep_Block	25%tile - - Median - - 75%tile	25%tile - - Median - - 75%tile
1	1	1.1714--3.5961--4.8157	1.4176--2.5847--4.9872
	2	1.2885--2.2251--4.5149	1.2163--3.2576--4.2366
	3	1.1486--2.2934--3.4982	1.2392--2.7027--3.8958
2	1	0.8978--1.6565--2.8852	1.1042--1.5684--2.5721
	2	0.9405--1.7578--2.6603	1.1005--1.392--3.3969
	3	0.9614--1.4529--2.3637	1.1819--1.8077--3.2587

Object depth 40cm

Single image formation time (sec)			
		Matched	Unmatched
Session	Rep_Block	25%tile - - Median - - 75%tile	25%tile - - Median - - 75%tile
1	1	1.5534--2.2902--3.5106	1.4176--2.5847--4.9872
	2	1.2245--2.0668--3.2012	1.2163--3.2576--4.2366
	3	1.1025--2.1520--3.4180	1.2392--2.7027--3.8958
2	1	1.0126--1.8527--2.8108	1.1042--1.5684--2.5721
	2	0.9565--1.3471--2.8412	1.1005--1.392--3.3969
	3	1.0324--1.2387--2.6780	1.1819--1.8077--3.2587

Object depth 200cm

Single image formation time (sec)			
		Matched	Unmatched
Session	Rep_Block	25%tile - - Median - - 75%tile	25%tile - - Median - - 75%tile
1	1	1.1714--3.5961--4.8157	1.5146--3.6004--6.0727
	2	1.2885--2.2251--4.5149	2.3894--4.3512--6.6374
	3	1.1486--2.2934--3.4982	1.8613--3.2397--6.1447
2	1	0.8978--1.6565--2.8852	1.2150--1.4734--5.2966
	2	0.9405--1.7578--2.6603	1.2815--2.2011--5.5324
	3	0.9614--1.4529--2.3637	1.2263--2.6145--3.7099

Table 5.5. The summary of median and inter-quartiles of the time taken to form a single stereoscopic image of a virtual object of 10 participants (1 to 10). Groupings in object depth (40cm and 200cm), lens focus (40cm and 200cm) at 3 repeated blocks (1 to 3) and 2 sessions (1 to 2).

Generally, the median single formation times at the matched conditions were shorter than those at the respective unmatched conditions. In addition, it could be observed that there was a trend of median single image formation time decrease along rep_block in the matched conditions. At all the matched conditions, the median single image formation times at Rep_block 3 were always shorter than those at Rep_block 1.

However, at the unmatched conditions, a trend of median single image formation time decrease along rep_block could not be observed. The median single image formation times at Rep_block 3 actually were longer than those at Rep_block 1 in 3 of the 4 cases.

A trend of median single image formation time decrease along session could also be observed at both the matched and unmatched conditions. Additionally, it appeared that the trend of median single image formation time decrease along session was larger at the matched conditions than at the unmatched conditions.

5.5.2 Section Summary

The non-parametric analysis by Wilcoxon signed ranks test provided further support for the findings by the parametric analysis in Section 5.4. It was observed that the p-values of matching lens focus with object depth decreased along rep_block and session. This indicated that the effect of matching might not be observable at the beginning, but after a number of runs of single image formation tasks as the experiment progressed, the participants could increasingly benefit from the effect of matching lens focus with object depth.

In other words, the result suggested that even the participants could not form a single stereoscopic image faster at the matched condition than at the unmatched condition in the earlier runs, however after a number of runs it was found that they could benefit from the effect of matching. The implication was either immediately or in the long run, the effect of matching could benefit the participants in forming a single stereoscopic image.

For the absolute single image formation time, the obvious reduction of the median single image formation times along rep_block and session at the matched conditions could be an explanation to the increasing significance of the matching effect, since the difference between time in the matched condition and time in the unmatched condition was enlarged.

The result suggested that in the matched conditions participants generally had longer single image formation time at the beginning and after runs of single image formation, the single image formation time become shorter and shorter. This might be explained by the existence of the adaptation effect (a physiological effect) or the learning effect (a psychological effect) that could reduce the single image formation time after a number of runs.

5.6 Chapter Summary

Matching lens focus with object depth has been shown to significantly reduce the single image formation time in most cases. In particular, hypotheses H1, H3, and H4 have been proven to be true and hypothesis H2 has been rejected. For H2, a trend has been identified to suggest that as the number of repetition increases, H2 will become true after about three repeated blocks of single image formation tasks. With the supportive findings from the non-parametric tests, it could be concluded that matching lens focus with object depth can reduce single image formation times.

Given the trend that the benefits of matching lens focus with object depth will increase with increasing repetitions, it would be reasonable to expect the benefit of the reduction of single image formation time by matching lens focus with object depth would also be present in formal industrial and training tasks. In this study, each participants only need to form a single stereoscopic image 120 times but in industrial training tasks, it is likely that operators will need to form a single stereoscopic image hundred of times per task, or even thousand of times at their operations in the long run.

6 Effects of Participants' Visual Parameters and their Relationships with Individual Performance

6.1 Overview

In Section 5.4, the comparison of the ANOVA and paired t test results at the four split data sets exposed the effects of participant. There was possible performance variation among the participants. The objective of this chapter is to report the individual performance of the 10 participants on the single image formation times.

The formation of a single stereoscopic image involves a series of ocular processes. It is hypothesized that the execution and speed of these ocular processes determine the single image formation time. It is thought that some visual parameters can reflect the ability to perform these ocular processes. These visual parameters can have relationships with the participants' performance.

A number of visual parameters of the participants, which were related to the eyes' vergence, were measured by a registered optometrist. A series of observations and statistical tests were performed on the data to investigate the relationship between the individuals' performance and these visual parameters. Effort would also be made to study if there was any relationship between the effect of matching to the individuals and the visual parameters.

6.2 Effects of Visual Parameters

6.2.1 Discussion of Effects of Visual Parameters on Findings in Chapter 5

One of the major findings obtained in Chapter 5 was the single image formation times in the matched conditions, Condition 1 and Condition 4, were significantly shorter than in Condition 3; but were not significant different from the single image formation time in Condition 2. The explanation would be related to the difference of ocular processes in each condition.

The ocular processes in the formation of a single stereoscopic image in each condition were introduced in Chapter 4 and were re-visited.

Condition 1 (Lens focus: 40cm; Object depth: 40cm):

The participants converged to 40cm. No fusional convergence was used.

Condition 2 (Lens focus: 200cm; Object depth: 40cm):

The participants converged to 40cm. Positive fusional convergence was used.

Condition 3 (Lens focus: 40cm; Object depth: 200cm):

The participants converged to 200cm. Negative fusional convergence was used.

Condition 4 (Lens focus: 200cm; Object depth: 200cm):

The participants converged to 200cm. No fusional convergence was used.

In the two matched conditions, Condition 1 and 4, it was not necessary to utilize any fusional convergence ability. The use of extra fusional convergence ability could be the difference between the matched conditions and unmatched conditions. It was possible that the utilization of extra fusional convergence or divergence (i.e. negative convergence) ability took time, or required effort, or was related certain difficulty, and that led to a longer single image formation time.

Additionally, in the two unmatched conditions, the difference of the ocular process was that Condition 2 needed positive fusional convergence but Condition 3 needed negative fusional convergence. It was possible that Condition 3 had significantly longer single image formation time than Condition 2 because of this difference. This is supported by the fact that for human eyes, the extent of negative fusional convergence is much smaller than positive fusional convergence (Tunnacliffe, 1993). Since the strength of fusion by divergence is much weaker than the strength of fusion by convergence, it can be expected that it is more difficult to diverge from 40cm to 200cm than converge from 200cm to 40cm. This was a possible reason for the significant difference of single image formation times between Condition 2 and 3.

In addition, it was thought that if the participants had a sufficient amount of fusional convergence ability, they might be able to easily converge from 200cm to 40cm in Condition 2. This could be a reason for no significant difference of single image formation times between the Condition 1 and 4 (matched conditions) and Condition 2 (unmatched condition).

6.2.2 Selection of Visual Parameters to be Studied

Since the ability of positive and negative fusional convergence appeared to be possible to influence the individual, the participants' positive fusional reserve (the amount of convergence movement to maintain fusion, i.e. measuring the ability of positive fusional convergence) and negative fusional reserve (the amount of divergence movement to maintain fusion, i.e. measuring the ability of negative fusional convergence) would be studied.

It is also felt important to study other visual parameters that are related to the vergence of human eyes. Lateral phoria, a latent squint which is a condition of motor imbalance of the eyes, would be studied. The linkage of lateral phoria to the study is that those who have lateral phoria will experience a condition that the active position of the eyes coincides with the fixation position, but the passive fusion-free position deviates from it. A fusional effort has to be exerted so as to obtain binocular fixation (Costello and Howarth, 1996). As lateral phoria required the people to use a certain amount of fusional ability, this visual parameter will be studied to see its influence.

People who have exophoria means their latent squint is diverging, and they need to exert positive fusional convergence ability to obtain binocular fixation. Alternatively, people who have esophoria means their latent squint is converging, and so they need to exert negative fusional convergence ability to obtain binocular fixation.

Two hypotheses about the relationship between visual parameters and the single image formation time were established:

- H5: Greater the fusional reserve would lead to shorter single image formation time, since participants who had greater fusional reserve were expected to have a larger allowable vergence ability to perform the ocular processes in forming a single stereoscopic image in the experiment task.

- H6: Smaller lateral phoria would lead to smaller single image formation time, since participants who had smaller lateral phoria were expected to spend less vergence ability to maintain binocular fixation and so more remaining vergence ability could assist the performance of the ocular processes in forming a single stereoscopic image in the experiment task.

The fusional reserves and lateral phoria of the participants were measured one time by a registered optometrist. These visual parameters at both near and distance were measured because there were near and far viewing conditions in the experiment. The test distance at distance or near of each test followed the standard optometry measurement procedures. The detailed visual parameters that were measured were:

- Negative fusional reserve at distance (6m)
- Negative fusional reserve at near (40cm)
- Positive fusional reserve at distance (6m)
- Positive fusional reserve at near (40cm)
- Lateral phoria at distance (3m)

Lateral phoria at near (1/3m i.e. 33cm)

A summary of the measurement results was listed in Table 6.1.

Visual Parameters	Range (prism diopter)	Mean (prism diopter)	Standard deviation (prism diopter)
Negative fusional reserve at distance (10 data)	8 to 22	15.1	5.04
Negative fusional reserve at near (10 data)	14 to 34	22.8	6.76
Positive fusional reserve at distance (10 data)	16 to 30	24.1	4.72
Positive fusional reserve at near (9 data)	14 to 38	24.1	8.08
Lateral phoria at distance (10 data)	-5 to 1	-0.9	1.66
Lateral phoria at near (10 data)	-8 to 4	-0.6	3.44

Table 6.1 The range, mean and standard deviation of the measurement results at six types of fusioanl reserve and lateral phoria parameters at 10 participants. Unit in prism diopter. For positive fusional reserve at near there are only 9 data from 9 participants, since one participant was unable to perform that measurement test.

6.3 Interaction between Effect of Participant and Effect of Matching Lens Focus with Object Depth

4 different interaction plots were plotted on data sets grouped by lens focus 40cm, lens focus 200cm, object depth 40cm and object depth 200cm. The individual performance in the single stereoscopic image formation and the effect of matching to the individuals could be inspected.

6.3.1 Findings

6.3.1.1 Interaction on Data of Lens Focus 40cm

Different participants' performance was observed. It appeared that their performance could be divided into three groups. P6, 9 and 10 had smaller median single image formation time in the unmatched condition, and had a small reduction of single image formation time in the matched condition. P1, 2, 5 and 8 had larger median single image formation time in the unmatched condition, and had a relatively large reduction of single image formation time in the matched condition. P3, 4 and 7 had medium median single image formation time in the unmatched condition, and had small reduction of single image formation time in the matched condition.

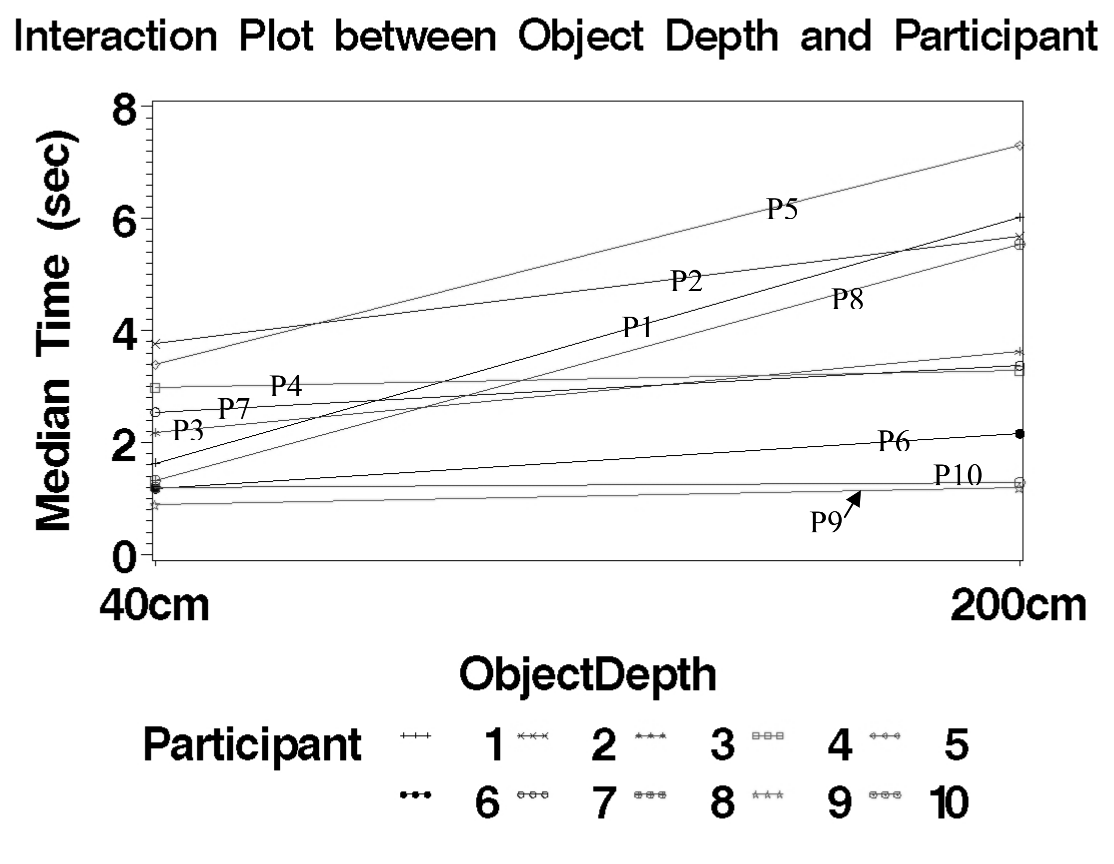

Fig 6.1 An interaction plot between the main effects of object depth (40cm and 200cm) and the main effects of participant (1 to 10) on the median single time formation time at lens focus 40cm.

6.3.1.2 Interaction on Data of Lens Focus 200cm

Again it appeared that the participants' performance could be divided into three groups. P1, 6, 8, 9 and 10 had smaller median single image formation time in the unmatched condition, and had relatively smaller reduction in the matched condition.

P2 and 5 had larger median single image formation time in the unmatched condition, and had larger reduction in the matched condition. P3, 4 and 7 had medium median single image formation time in the unmatched condition, but P4 only had slight reduction in the matched condition and P3 and 7 even had increase of median single image formation time in the matched condition.

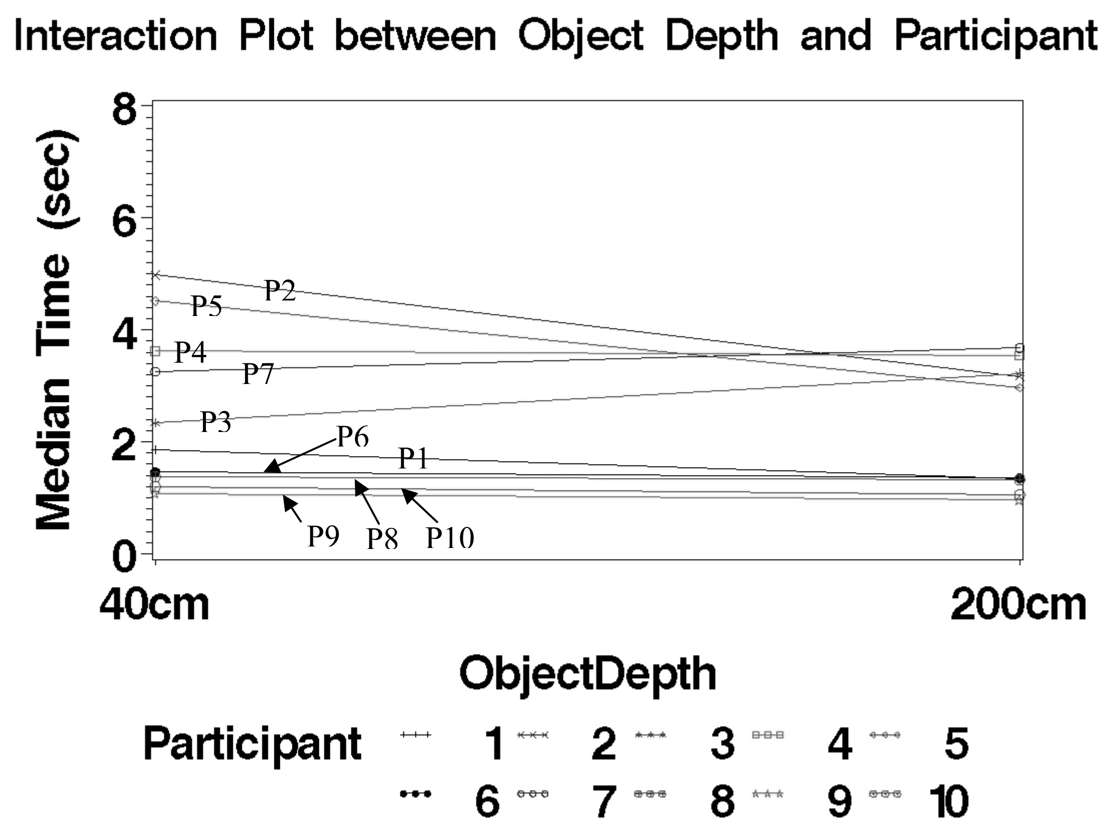

Fig 6.2 An interaction plot between the main effects of object depth (40cm and 200cm) and the main effects of participant (1 to 10) on the median single time formation time at lens focus 200cm.

6.3.1.3 Interaction on Data of Object Depth 40cm

Generally the participants showed a reduction of median single image formation time when the lens focus matched with the object depth. Generally the reduction in median single image formation time appeared a uniform pattern since there was nearly no crossing of the data lines on the plot. The data lines did not obviously indicate two groups of participants' performance.

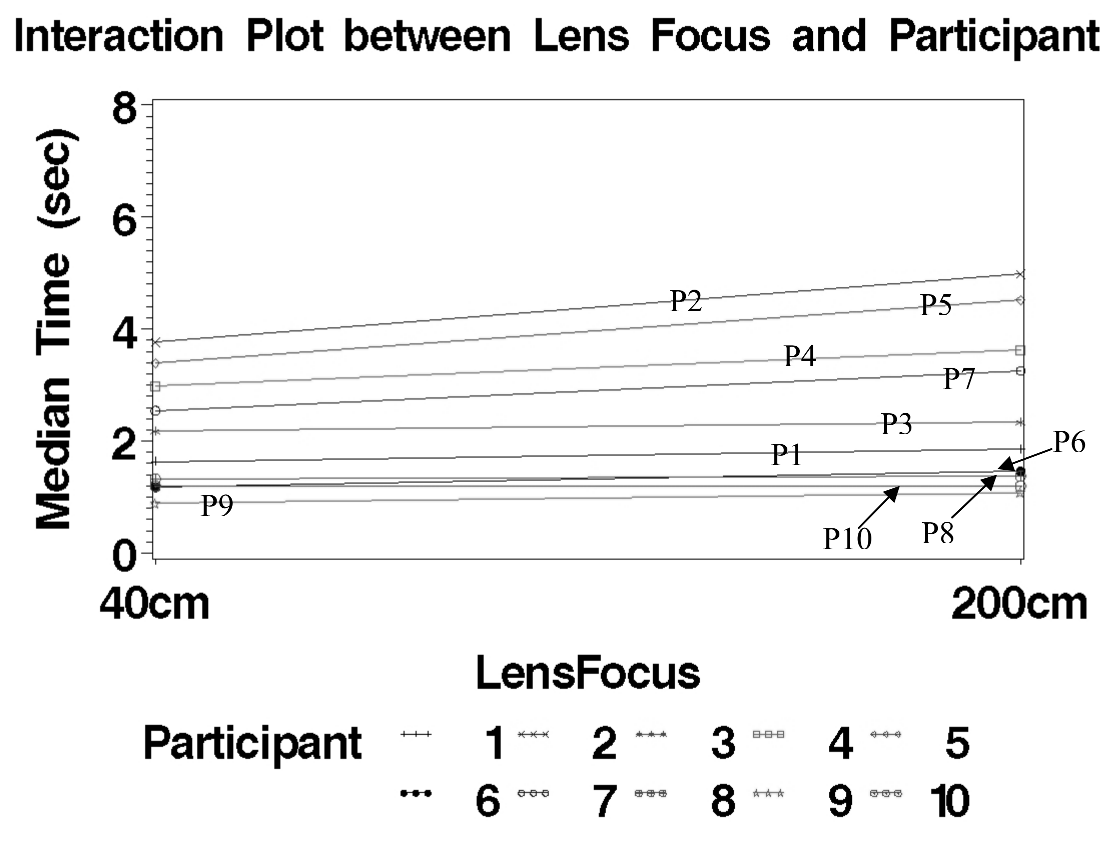

Fig 6.3 An interaction plot between the main effects of lens focus (40cm and 200cm) and the main effects of participant (1 to 10) on the median single time formation time at object depth of 40cm.

Roughly speaking, P1, 3, 6, 8, 9, 10 had comparably (with the other four participant) smaller single image formation time at the unmatched condition. At the matched condition they showed a small reduction of single image formation time. On the other hand, P2, 4, 5, 7 had larger single image formation time at the unmatched condition and had a comparably larger reduction of single image formation time at the matched condition.

6.3.1.4 Interaction on Data of Object Depth 200cm

The participants' performance was very similar as in the interaction plot on data of which lens focus was fixed at 40cm. The participants' performance showed observable variance and appeared that they could be divided into three groups. P6, 9 and 10 had smaller median single image formation time in the unmatched condition, and had small reduction in the matched condition. P1, 2, 5 and 8 had larger median single image formation time in the unmatched condition, and had large reduction in matched condition. P3, 4 and 7 had medium median single image formation time in the unmatched condition, but P3 had a small reduction in the matched condition only and P4 and 7 even had increase of median single image formation time in the matched condition.

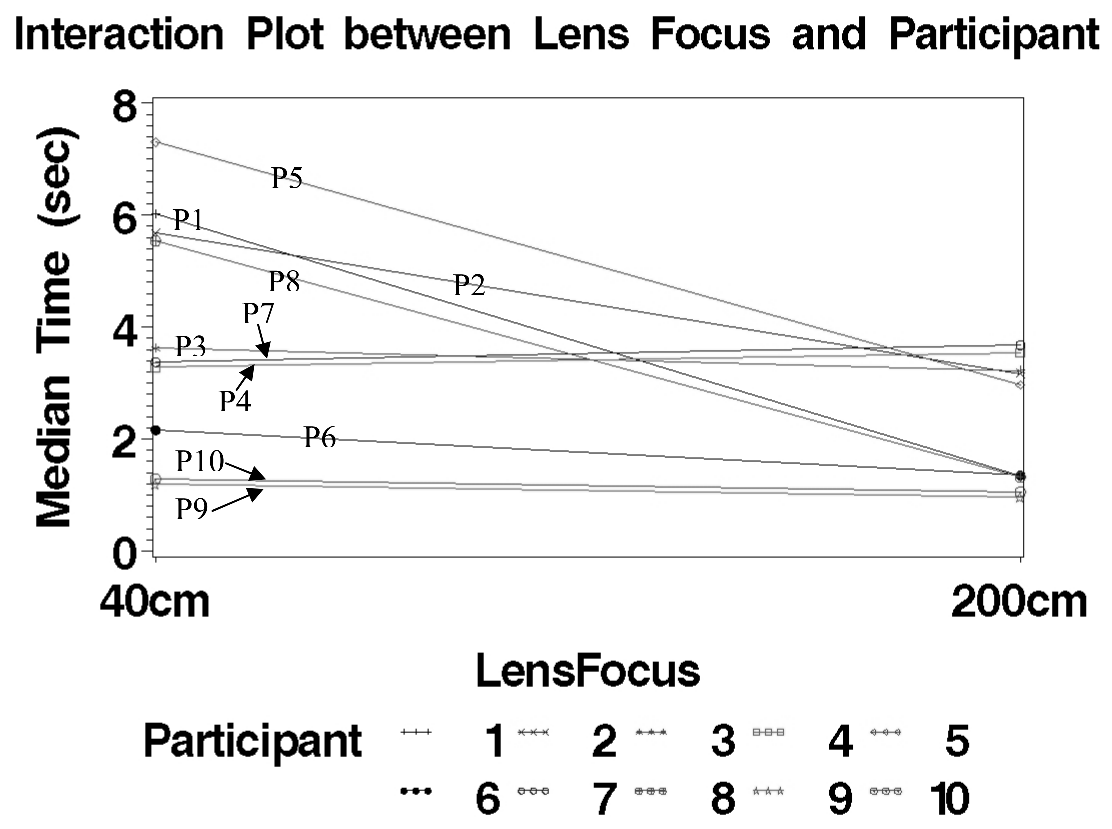

Fig 6.4 An interaction plot between the main effects of lens focus (40cm and 200cm) and the main effects of participant (1 to 10) on the median single time formation time at object depth of 200cm.

6.3.2 Section Summary

Inspections of the individual data suggest that seven participants appeared to receive benefit from the matching of lens focus with object depth to different extents. The other three participants (namely P3, 4 and 7) appear not to benefit from this matching.

The consistency of the participants' performance across various repetitions could be observed in general. For example, P6, 9, 10 tended to have smaller median single image formation time in the unmatched condition, and have a small reduction in the matched condition. On the other hand, P2 and 5 tended to have a larger median single image formation time in the unmatched condition, and have a larger reduction in matched condition. Conversely, P3, 4 and 7 did not appear to have benefited from the matching.

It is suspected that the individual visual parameters of the participants could be the cause to the participants' performance. This is analyzed and discussed in the subsequent sections. The objective is to identify possible relationships between the individual visual parameters and performance that can explain the observed variations of the matching effect on the individuals and also the variation in the single image formation times.

6.4 Relationship between Visual Parameters and Individual Effects of Matching

Section 6.3 presented the variation of the effects of matching lens focus with object depth on the individuals by the method of graphical inspection. In this section, the issue is studied using statistical methods.

6.4.1 Individual Effects of Matching

Firstly, Wilcoxon signed ranks test run by SPSS was used to examine the effect of matching on the individuals. The test was performed on the 24 single image formation time data points for each participant (i.e. 12 single image formation time data points obtained at the matched condition and 12 data points at the unmatched condition).

Test Statistics(b)

	P1_unmatch - P1_match	P2_unmatch - P2_match	P3_unmatch - P3_match	P4_unmatch - P4_match	P5_unmatch - P5_match
Z	-2.314(a)	-3.657(a)	-.971(a)	-1.029(a)	-4.114(a)
Asymp. Sig. (2-tailed)	.021	.000	.331	.304	.000

a Based on negative ranks.
b Wilcoxon Signed Ranks Test

	P6_unmatch - P6_match	P7_unmatch - P7_match	P8_unmatch - P8_match	P9_unmatch - P9_match	P10_unmatch - P10_match
Z	-4.000(a)	-.800(a)	-3.114(a)	-4.171(a)	-3.072(a)
Asymp. Sig. (2-tailed)	.000	.424	.002	.000	.002

Table 6.2 Wilcoxon signed ranks test results on the effect of matching lens focus with object depth to the single image formation time at 10 participants individually.

The order of the experimental condition presentation is found to be uncorrelated with the single image formation time ($p>0.3$), therefore the Wilcoxon signed ranks test results would not be affected by the order of the condition presentation in the experiment.

The results of the signed ranks tests show that the ranks of single image formation times at the matched condition shorter than those at the unmatched condition are always higher than the ranks of times at the unmatched condition shorter than those at the matched condition. In other words, all the participants had shorter single image formation time at the matched conditions. However, not every participant shows a significant reduction of single image formation time.

Table 6.2 indicates that the effect of matching lens focus with object depth is significant ($p<0.05$) for the data collected from participants P1, 2, 4, 5, 6, 8, 9, 10. On the other hand, the effect of matching is not significant ($p>0.05$) for the data collected from P3, P4, P7. Therefore in terms of the matching effect, the findings from the statistical analysis are consistent with the observations of the interaction plots.

6.4.2 Correlation between the Z-statistics on Individual Effects of Matching and Their Visual Parameters

In the next step, the bivariate correlation between the effect of matching on the individual participants and their visual parameters was investigated. Correlations between the p-value and Z-statistics of the effect of matching obtained in Table 6.2 and the six types of visual parameters mentioned in Section 6.2.2 have been analyzed.

Correlations

Spearman's rho		p_value_matching	Z_statistcs_matching
Negative fusional reserve at distance	Correlation Coefficient	-.366	-.274
	Sig. (2-tailed)	.298	.443
	N	10	10
Positive fusional reserve at distance	Correlation Coefficient	.145	.262
	Sig. (2-tailed)	.689	.464
	N	10	10
Negative fusional reserve at near	Correlation Coefficient	-.164	-.140
	Sig. (2-tailed)	.651	.699
	N	10	10
Positive fusional reserve at near	Correlation Coefficient	.533	.644
	Sig. (2-tailed)	.139	.061
	N	9	9
Lateral phoria at distance	Correlation Coefficient	.495	.481
	Sig. (2-tailed)	.146	.159
	N	10	10
Lateral phoria at near	Correlation Coefficient	-.149	-.075
	Sig. (2-tailed)	.681	.837
	N	10	10

* Correlation is significant at the 0.05 level (2-tailed).

Table 6.3 Results of the correlation analyses between the p-value and Z-statistics of the effect of matching to the 10 individual participants and the 6 types of visual parameters. 10 data in each correlation analysis.

No significant correlation is found although some trends are observed about the positive and negative fusional reserves. The correlation coefficients link with the two negative fusional reserves at distance and at near are both negative. The negative correlation coefficients mean that the greater the negative fusional reserve, the smaller the p-value and Z statistic; in other words, the greater the effects of matching.

It is found that the correlation coefficients linked with the two positive fusional reserves at distance and at near are both negative. The positive correlation coefficients mean that the greater the positive fusional reserve, the greater the p-value and Z statistic; in other words, the smaller the effect of matching.

6.4.3 The Search of Extreme Visual Parameters among Participants with Different Effects of Matching

Further analyses have been conducted to identify any special difference of visual parameters between P3, 4, 7 (effects of matching are insignificant) and P1, 2, 4, 5, 6, 8, 9, 10 (effects of matching are significant).

It has been observed that the negative fusional reserve at distance showed a comparably larger difference between the two groups of participants. P3, 4, 7 had the three smallest values of negative fusional reserve at distance.

To compare the extreme cases, data collected from P3 and P4 have been grouped together as they have the two smallest negative fusional reserve at distance. Data collected from P1 and P10 have also been grouped together as they have the two greatest negative fusional reserve at distance. Results of Wilcoxon signed ranks tests indicate that the effects of matching on single image formation times from P1 and P10 are significant (p=0.02), but the similar effects are not significant with the data from P3 and P4 (p=0.163).

Test Statistics(b)

	P1&10_unmatch - P1&10_match	P3&4_unmatch - P3&4_match
Z	-3.079(a)	-1.395(a)
Asymp. Sig. (2-tailed)	.002	.163

a Based on negative ranks.
b Wilcoxon Signed Ranks Test

Table 6.4 Wilcoxon signed ranks test results on the effects of matching lens focus with object depth on the single image formation time at (1) data set that groups data of P1 and P10 (2) data set that groups the data of P3 and P4. In each data set there are 48 single image formation time data points, of which 24 data points obtained at the matched condition, and 24 data points obtained at the unmatched condition).

This time, P3, 4, 7 and 9 were grouped together as they had the four smallest negative fusional reserve at distance. In opposite, P1, 10, 6 and 8 were as together. Wilcoxon signed ranks tests show that both groups indicate significant effects of matching.

Test Statistics(b)

	P1_10_6_8_unmatch - P1_10_6_8_match	P3_4_7_9_unmatch - P3_4_7_9_match
Z	-5.724(a)	-2.684(a)
Asymp. Sig. (2-tailed)	.000	.007

a Based on negative ranks.
b Wilcoxon Signed Ranks Test

Table 6.5 Wilcoxon signed ranks test results on the effects of matching lens focus with object depth to the single image formation time at (1) data set that groups data of P1, 10, 6 and 8 (2) data set that groups data of P3, 4, 7 and 9. In each data set there are 96 single image formation time data points, of which 48 data points obtained at the matched condition, and 48 data points obtained at the unmatched condition).

Up to this point, it was unable to determine any strong relationship between the effects of matching lens focus with object depth on the individuals and their visual parameters.

6.5 Relationship between Visual Parameters and Individual Performance of Absolute Single Image Formation Time

This analysis aims to explain the individual difference in the absolute single image formation time of the 10 participants. The correlation between the visual parameters and the absolute single image formation times at Condition 1, 2, 3 and 4 are analyzed.

6.5.1 Findings on Fusional Reserve

Firstly, correlation analyses have been conducted between the absolute single image formation time of the 10 individuals in Condition 1, 2, 3 and 4 and the 4 types of fusional reserve. The number of data points used for each condition in the correlation analyses is 60 representing the data collected from 10 participants in 3 rep_blocks and 2 sessions. Significant correlations have been found between the single image formation times and the negative fusional reserves. In particular, negative fusional reserve at distance is significantly correlated with the single image formation times in Condition 1, 2 and 4, whilst negative fusional reserve at near is significantly correlated with the single image formation times in Condition 1, 2, 3 and 4.

Correlations

Spearman's rho		Time in Condition 1	Time in Condition 2	Time in Condition 3	Time in Condition 4
Negative fusional reserve at distance	Correlation Coefficient	-.276(*)	-.287(*)	-.177	-.529(**)
	Sig. (2-tailed)	.033	.026	.177	.000
	N	60	60	60	60
Positive fusional reserve at distance	Correlation Coefficient	.234	.245	.163	.183
	Sig. (2-tailed)	.071	.059	.213	.161
	N	60	60	60	60
Negative fusional reserve at near	Correlation Coefficient	-.397(**)	-.405(**)	-.278(*)	-.456(**)
	Sig. (2-tailed)	.002	.001	.032	.000
	N	60	60	60	60
Positive fusional reserve at near	Correlation Coefficient	.046	-.035	.072	.082
	Sig. (2-tailed)	.743	.804	.603	.554
	N	54	54	54	54

** Correlation is significant at the 0.01 level (2-tailed).
* Correlation is significant at the 0.05 level (2-tailed).

Table 6.6 Results of the correlation analyses between the absolute single image formation time of the 10 individual participants in Condition 1, 2, 3 and 4 and the 4 types of fusional reserve. 60 data points in each analysis, which is the data in the 3 rep_block and 2 sessions of the 10 participants in each condition.

The correlation analyses have been repeated using the average single image formation times over the 2 sessions. In other words, for each condition, the number of data points for each condition reduces to 30 representing the data collected from the 10 participants in the three rep_blocks (averaged over the 2 sessions). Results of correlation analyses indicates that the negative fusional reserve at distance remains significantly correlated with the single image formation times in Condition 4, whilst the negative fusional reserve at near remains significantly correlated with the single image formation times in Condition 1, 2 and 4.

Correlations

Spearman's rho		Time in Condition 1	Time in Condition 2	Time in Condition 3	Time in Condition 4
Negative fusional reserve at distance	Correlation Coefficient	-.342	-.340	-.134	-.524(**)
	Sig. (2-tailed)	.064	.066	.479	.003
	N	30	30	30	30
Positive fusional reserve at distance	Correlation Coefficient	.271	.265	.206	.291
	Sig. (2-tailed)	.147	.157	.275	.119
	N	30	30	30	30
Negative fusional reserve at near	Correlation Coefficient	-.441(*)	-.467(**)	-.250	-.439(*)
	Sig. (2-tailed)	.015	.009	.182	.015
	N	30	30	30	30
Positive fusional reserve at near	Correlation Coefficient	.018	-.049	.164	.139
	Sig. (2-tailed)	.931	.808	.415	.490
	N	27	27	27	27

** Correlation is significant at the 0.01 level (2-tailed).
* Correlation is significant at the 0.05 level (2-tailed).

Table 6.7 Results of the correlation analyses between the absolute single image formation time of the 10 individual participants in Condition 1, 2, 3 and 4 and the 4 types of fusional reserve. 30 data points in each analysis, which is the averaged data (over the 2 sessions) for the 3 rep_blocks of the 10 participants in each condition.

The data was further reduced by averaging the data in the 3 rep_blocks into 1 data. This gives only 10 data points for each condition representing the data collected from the 10 participants in each condition. This time, no significant correlation has been found.

Correlations

Spearman's rho		Time in Condition 1	Time in Condition 2	Time in Condition 3	Time in Condition 4
Negative fusional reserve at distance	Correlation Coefficient	-.335	-.341	.098	-.585
	Sig. (2-tailed)	.343	.334	.789	.075
	N	10	10	10	10
Positive fusional reserve at distance	Correlation Coefficient	.256	.250	.122	.341
	Sig. (2-tailed)	.475	.486	.737	.334
	N	10	10	10	10
Negative fusional reserve at near	Correlation Coefficient	-.500	-.494	-.207	-.427
	Sig. (2-tailed)	.141	.147	.565	.219
	N	10	10	10	10
Positive fusional reserve at near	Correlation Coefficient	.008	-.075	.184	.201
	Sig. (2-tailed)	.983	.847	.635	.604

Table 6.8 Results of the correlation analyses between the absolute single image formation time of the 10 individual participants in Condition 1, 2, 3 and 4 and the 4 types of fusional reserve. 10 data points in each analysis, which is the averaged data (over the 3 rep_blocks and 2 sessions) of the 10 participants in each condition.

It appeared that in general, participants with greater negative fusional ability could form a single stereoscopic image faster, both in the matched and unmatched conditions. This supports the hypothesis H5 stated previously in Section 6.2.2.

6.5.2 Findings on Lateral Phoria

Similarly, correlation analyses have been conducted between the absolute single image formation time of the 10 individual participants in Condition 1, 2, 3 and 4 and the 2 types of lateral phoria. The number of data points for each condition is 60 representing the data collected from the 10 participants in the three rep_block and two sessions. Lateral phoria at near has been found to significantly correlate with the single image formation time in Condition 2 (p=0.029, Table 6.9).

Correlations

Spearman's rho		Time in Condition 1	Time in Condition 2	Time in Condition 3	Time in Condition 4
Lateral phoria at distance	Correlation Coefficient	-.098	-.142	.098	-.030
	Sig. (2-tailed)	.454	.278	.458	.818
	N	60	60	60	60
Lateral phoria at near	Correlation Coefficient	.190	.281(*)	.128	.206
	Sig. (2-tailed)	.147	.029	.331	.115
	N	60	60	60	60

* Correlation is significant at the 0.05 level (2-tailed).

Table 6.9 Results of the correlation analyses between the absolute single image formation time of the 10 individual participants in Condition 1, 2, 3 and 4 and the 2 types of lateral phoria. 60 data points in each analysis, which is the data in the 3 rep_block and 2 sessions of the 10 participants in each condition.

The data are further reduced by averaging the data in the 2 sessions. The number of data points for each condition become 30 representing the data collected from the 10 participants in the 3 rep_blocks. Only marginal significant correlation is found between the lateral phoria at near and the single image formation times ($p<0.1$, Table 6.10).

Correlations

Spearman's rho		Time in Condition 1	Time in Condition 2	Time in Condition 3	Time in Condition 4
Lateral phoria at distance	Correlation Coefficient	-.099	-.111	.184	.044
	Sig. (2-tailed)	.603	.559	.330	.817
	N	30	30	30	30
Lateral phoria at near	Correlation Coefficient	.228	.314	.084	.282
	Sig. (2-tailed)	.225	.091	.660	.132
	N	30	30	30	30

Table 6.10 Results of the correlation analyses between the absolute single image formation time of the 10 individual participants in Condition 1, 2, 3 and 4 and the 2 types of lateral phoria. 30 data points in each analysis, which is the averaged data with respect to rep_block in 2 sessions of the 10 participants in each condition.

The data have been further reduced by averaging the 6 data points collected in the 6 repeated runs (3 rep_blocks and 2 sessions) into 1 data point. The number of data point become 10. No significant correlation result is found (Table 6.11).

Correlations

Spearman's rho		Time in Condition 1	Time in Condition 2	Time in Condition 3	Time in Condition 4
Lateral phoria at distance	Correlation Coefficient	-.146	-.133	.266	.165
	Sig. (2-tailed)	.688	.714	.457	.649
	N	10	10	10	10
Lateral phoria at near	Correlation Coefficient	.238	.356	-.019	.319
	Sig. (2-tailed)	.509	.312	.959	.369
	N	10	10	10	10

Table 6.11 Results of the correlation analyses between the absolute single image formation time of the 10 individual participants in Condition 1, 2, 3 and 4 and the 2 types of lateral phoria. 10 data points in each analysis, which is the averaged data with respect to rep_block and session of the 10 participants in each condition.

The analyses are repeated again in order to test H6. Because H6 concerns about the effect of the magnitude of the lateral phoria, the absolute value of the lateral phoria data is taken in the analyses.

Lateral phoria at near has been found to significantly correlate with the single image formation time in Condition 1 (p=0.038, Table 6.12) and Condition 4 (p=0.038, Table 6.12). The positive correlation supports the hypothesis H6 made earlier in Section 6.2.2 for the matched conditions.

Correlations

Spearman's rho		Time in Condition 1	Time in Condition 2	Time in Condition 3	Time in Condition 4
Lateral phoria at distance	Correlation Coefficient	-.006	.016	-.138	-.175
	Sig. (2-tailed)	.963	.901	.294	.181
	N	60	60	60	60
Lateral phoria at near	Correlation Coefficient	.268*	.190	.051	.263*
	Sig. (2-tailed)	.038	.147	.700	.042
	N	60	60	60	60

* Correlation is significant at the 0.05 level (2-tailed).

Table 6.12 Results of the correlation analyses between the absolute single image formation time of the 10 individual participants in Condition 1, 2, 3 and 4 and the absolute values of the 2 types of lateral phoria. 60 data points in each analysis, which is the data in the 3 rep_block and 2 sessions of the 10 participants in each condition.

The data are further reduced by averaging the data in the 2 sessions. The number of data points for each condition become 30 representing the data collected from the 10 participants in the 3 rep_blocks. No significant correlation result is found (Table 6.13).

Correlations

Spearman's rho		Time in Condition 1	Time in Condition 2	Time in Condition 3	Time in Condition 4
Lateral phoria at distance	Correlation Coefficient	.121	.142	.228	.159
	Sig. (2-tailed)	.525	.454	.225	.402
	N	30	30	30	30
Lateral phoria at near	Correlation Coefficient	.151	.223	.309	.102
	Sig. (2-tailed)	.425	.237	.097	.592
	N	30	30	30	30

Table 6.13 Results of the correlation analyses between the absolute single image formation time of the 10 individual participants in Condition 1, 2, 3 and 4 and the absolute values of the 2 types of lateral phoria. 30 data points in each analysis, which is the averaged data (over the 2 sessions) for the 3 rep_blocks of the 10 participants in each condition.

The data have been further reduced by averaging the 6 data points collected in the 6 repeated runs (3 rep_blocks and 2 sessions) into 1 data point. The number of data point become 10. No significant correlation result is found (Table 6.14).

Correlations

Spearman's rho		Time in Condition 1	Time in Condition 2	Time in Condition 3	Time in Condition 4
Lateral phoria at distance	Correlation Coefficient	.045	-.058	-.175	-.414
	Sig. (2-tailed)	.901	.873	.630	.235
	N	10	10	10	10
Lateral phoria at near	Correlation Coefficient	.289	.257	-.144	.213
	Sig. (2-tailed)	.419	.473	.691	.554
	N	10	10	10	10

Table 6.14 Results of the correlation analyses between the absolute single image formation time of the 10 individual participants in Condition 1, 2, 3 and 4 and the absolute values of the 2 types of lateral phoria. 10 data points in each analysis, which is the averaged data (over the 3 rep_blocks and 2 sessions) of the 10 participants in each condition.

The difference between the analyses using real values and absolute value of the lateral phoria data reflects that there is possible interaction effect between the direction of the two types of lateral phoria (i.e. exophoria and esophoria) and different viewing conditions on the single image formation time.

6.6 Discussions on Findings

Individual variations of the effects of matching lens focus with object depth have been identified. Among the ten participants, seven participants consistently and significantly benefited from the effect of matching but three participants did not.

For some conditions, significant correlations have been observed between the absolute single image formation times and the negative fusional reserve and lateral phoria parameters of the participants. Referring to Table 6.6, negative fusional reserve at near has been found to significantly correlate with the single image formation times in Conditions 1, 2, 3 and 4. Positive fusional reserve at distance significantly correlates with single image formation times in Conditions 1, 2 and 4. Referring to Table 6.12, near lateral phoria is significantly correlated with the single image formation time in Condition 1 and 4.

The significant results indicate that the performance of forming a single stereoscopic image is significantly related to the individual negative fusional reserve. Since the negative fusional reserve reflects one's ability to verge with greater negative fusional reserve reflects better ability to verge, participants with greater negative fusional reserve could form a single stereoscopic image faster. This is indeed statistically proven in this study. However, because the study only has 10 participants, the author hesitates to draw firm conclusion at this stage.

This study also observes that visual parameters could affect the individuals' absolute single image formation time while not affecting the effects of matching on individuals. A possible explanation is that those visual parameters affected the absolute single image formation time in the same way in both the matched and unmatched conditions. As such the effect of visual parameters was not apparent when the effect of matching was studied by comparing or ranking the matched conditions' data and the unmatched conditions' data.

7 Discussion, Recommendations and Conclusions

7.1 Discussion

7.1.1 Fulfillment of the Research Purposes

In Chapter 1, two research objectives are listed: (1) Study the benefits of matching lens focus with stereoscopic depth cues on the single image formation time; (2) prototype a micro-display system with dynamically adjustable lens focus. The work of this thesis fulfills both research objectives. The contribution are discussed in the following sections.

7.1.1.1 Benefits of Matching Lens Focus with Stereoscopic Depth Cues (Object Depth)

This thesis provides empirical evidence to support that matching lens focus with stereoscopic depth cues (object depth) can significantly reduce the single image formation time when viewing a binocular micro-display. These increases have been identified to be associated with the unnatural demand for the eyes to diverge or converge. In particular, the unnatural demand for the eyes to diverge has been identified to be a more significant factor associated with increased period of double images when viewing stereoscopic images (Section 5.4.1).

In addition, this thesis found that repeated session and gender also have significant main effects. Participants took significantly shorter time to form single stereoscopic image in the second session and female could form single stereoscopic image faster than male participants. Effects of repeated session did not have significant interactions with the effects of matching lens focus with object depth. The interactions between the effects of matching lens focus with object depth and the effects of gender are discussed in Chapter 5.

The thesis also studies the individual variations on the absolute single image formation time and reports that three tenths of the participants' single image formation time data was not affected by matching lens focus with object depth. Interestingly, significant correlations between negative fusional reserve and lateral phoria parameters of the participants and the single image formation times have been identified.

7.1.1.2 Prototype a Micro-display System with Dynamically Adjustable Lens Focus

A micro-display system with dynamically adjustable lens focus was successfully prototyped for experimental use. It demonstrated the feasibility of developing the dynamically adjustable lens focus. The precise calibration and integration of the micro-displays and optics have been the major challenge. More details can be found in Chapter 3.

7.1.2 Implications of the Findings

The potential benefits of reducing the single image formation time by the means of matching lens focus with stereoscopic depth cues are mentioned in Chapter 5. In short, designers of binocular displays should avoid unnatural demand for the eyes to diverge. Although unnatural demand for the eyes to converge was not associated with the increases in the single image formation time in the beginning of the experiment, the benefit of matching became increasingly observable as the experiment progressed. Based on the observed trend, it was believed that the benefit of matching could carry on and the benefit would be particularly enjoyed by the frequent micro-display users.

This study used a binocular micro-display system in the experiment. Nevertheless, the findings of this study should not be limited to micro-display systems. Instead it can be applied on other types of binocular displays. The reason is that the problem of single stereoscopic image formation at other binocular displays is also related to the conflict between accommodation and vergence. In this thesis, the concept of matching lens focus with stereoscopic depth cues specifically tackles and eliminates the conflict between accommodation and vergence. Therefore the benefit of matching lens focus (or viewing distance, if the binocular system does not need a lens) with stereoscopic depth cues would be universal to all binocular displays.

The findings of this thesis provide supporting evidence to the benefits of matching lens focus with object depth. In particular, data indicate that unnatural demand for the eyes to diverge should be avoid while unnatural demand for the eyes to converge is undesirable. This study is complimentary to the development of various lens focus adjustment techniques (e.g., Rolland, 2000 and Shibata et al., 2004).

7.1.3 Limitations of the Study

In this study, only two levels of lens focus and object depth (40am and 200cm) have been studied. Also, the viewing task involves only stationary objects.

7.2 Recommendations for Future Study

After this study, the matching of lens focus with stereoscopic depth cues had been proven to be a solution to reduce single image formation time in situations under the context of this study. Since the study indicated significant benefit from the effect of matching, it is justified to extend this research to areas that have not been covered in this study to see if the benefit of matching still occurs in these areas.

7.2.1 Range of the Independent Variables

This study investigated the effect of matching lens focus with stereoscopic depth cues by an experiment using two levels (40cm and 200cm) at the independent variables. Taking into consideration that unnatural demand to diverge the eyes can cause longer periods of double images, it is questionable if the micro-display manufacturers should set the fixed lens focus to 3 ft or 2m. For instance, when viewers look at biocular images, the object depth becomes infinity. As a result viewers need to use negative fusional convergence to diverge from 3 ft or 200cm to infinity. This unnatural demand to diverge affects viewers' performance in forming a single stereoscopic image.

Future study can use a broader range and more levels at the independent variables (say adding 3 ft and 6m) in the experiment. This can further enhance the understanding of this topic.

7.2.2 Scope of the Experiment Task

The experiment task in this study simulated the fixation at far objects and near objects alternatively and simulated a reading task. Viewers only needed to form a single stereoscopic image on stationary virtual objects. As such, the scope of the study was limited to the single image formation time at the static condition of lens focus and stereoscopic depth cues.

Therefore, the effect of matching lens focus with stereoscopic depth cues has not been known in the dynamic situation, for instance the virtual object to be fused has a dynamically fore-and-aft movement. The dynamic movement makes the ocular processes different from those in this study, and the additional effect of the movement's range and velocity would increase the uncertainty of the performance. This is another area for future research.

7.2.3 Visual Parameters

The significant correlations between the single image formation times in some conditions and negative fusional reserve and lateral phoria parameters of the participants (Section 6.5) suggested that there could be some linkages between the individuals' performance and their visual parameters. This area was only briefly discussed in this study and there is room for further research. In addition, the individual difference of the effect of matching was not well understood. It is recommended that further study is needed in this area. If the individual variation in performance can be explained in future, a possible contribution is that a customized solution could be arranged to different viewers and all of them can have benefit of the reduction their single image formation time.

In future studies, individual variation in performance is expected to occur as has been the case in this study. If the variation needs to be examined, a measurement of visual parameters is suggested because this is a feasible direction to explain the individual variation.

7.2.4 The Possible Adaptation and Learning Effects

Chapter 5 mentioned that in the matched conditions, participants generally had longer single image formation time at the beginning and after runs of single image formation, the single image formation time become shorter and shorter. This might be explained by the existence of adaptation effect (physiological effect) or learning effect (psychological effect) that could reduce the single image formation time after a number of runs. These two effects can also be areas for further study.

7.2.5 Scale of the Experiment

For the experiment design, more sessions are recommended in order to study the effect of session.

In addition, more participants are recommended to study the effect of gender and visual parameters. At the same time, this allows the study to detect any possible relationship between gender and visual parameters. This could be helpful to explain the individual variation.

7.3 Conclusions

This thesis studies, for the first time, the effects of matching lens focus with stereoscopic depth cues (object depth) on the single image formation time when viewing a binocular micro-display. Results indicate that viewers will take significantly shorter time to form a single overlaid stereoscopic image when the lens focus are matched with the object depth ($p<0.05$, paired t test). Results from further examinations of the data suggest that unnatural demand for the eyes to diverge is associated with increases in the single image formation times. In other words, unnatural demand to diverge the eyes could cause longer periods of double images. Among the ten participants, seven consistently and significantly benefited from the effect of matching lens focus with stereoscopic depth cues but three viewers did not. Significant correlations have been observed between the single image formation times and the negative fusional reserve of the participants. The other findings include the significant effects of experiment session and gender. Future studies with more participants are recommended.

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Appendix A

Glossary of Terms

1. Terms related to the dynamically adjustable lens focus micro-display system and the virtual environment

Binocular images

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

Biocular images

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

Eye relief

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

Focal length of lens

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

Image distance

In a micro-display system, image distance is the distance between the magnified virtual image and the lens.

Inter-ocular distance (IOD)

The inter-distance between the centre of the left and right lens of the micro-display system.

Lens focus (also see image distance)

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

Lens formula

Describes the relationship between lens focus, object distance and focal length of the lens.

The formula is $1/u = 1/v + 1/f$

Where v = image distance, u = object distance, f = focal length of the lens.

Object depth

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

Object distance

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

Stereoscopic images

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

Stereoscopic depth cues

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

2. Terms related to the visual system

Accommodation

The adjustment of the lens's thickness of the eyes in order to achieve sharp vision.

Fusional reserve

Positive fusional reserve is the amount of convergence movement to maintain fusion. It represents the ability of positive fusional convergence.

Negative fusional reserve is the amount of divergence movement to maintain fusion. It represents the ability of negative fusional convergence.

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.

Vergence

There are two types of vergence: convergence and divergence.

Convergence is the inward turning movement of the eyes.

Divergence the outward turning movement of the eyes. Note that divergence is not necessarily a temporal movement. For instance, when the eyes verge from 40cm to 200cm, the action is also called divergence.

3. Terms related to the perception of the viewers in the experiment task

Single image (formed by viewer)

In this study, this term is referred to as the single image perceived by the viewers when they obtain single vision at a pair of biocular images.

Double images (formed by viewer)

In this study, this term is referred to as the images perceived by the viewers before they obtain single vision at either a pair of biocular images or binocular images.

Single stereoscopic image (formed by viewer)

In this study, it is referred to as the image perceived by the viewers when they obtain single vision at a pair of binocular images.

A single stereoscopic image (formed when viewing binocular images) is different from a single image (formed when viewing biocular images). Taking the binocular images used in the experiment as an example. There are two major stereoscopic objects, “DIST40” and “DIST200”. When the viewers are instructed to fixate at “DIST40”, they verge their eyes and obtain single vision on “DIST40”. However the viewers do not fuse “DIST200” of the left and right images into one, since “DIST40” and “DIST200” have a large difference in the object depth (40cm and 200cm respectively). In this case, the viewers, when successfully perceive a single stereoscopic image, actually see a fused “DIST40” object and two un-fused “DIST200” objects.

Appendix B

Experiment Procedure

1. Preparation

1.1. Obtain the consent of the participant

- 1.1.1. Explain the purpose and introduce the details of the experiment to the participant.
- 1.1.2. Explain the importance for his / her participation.
- 1.1.3. Ask the participant to fill in the Participant Information Sheet.
- 1.1.4. Ask the participant to read and sign the consent form.

1.2. Calm down period

- 1.2.1. Remind the participant if he/she needs to go to toilet.
- 1.2.2. Remind the participant not to drink too much water.
- 1.2.3. Remind the participant to turn off the mobile phone.
- 1.2.4. Make sure he/she did not take any drug within the last 24 hours.
- 1.2.5. Check if the participant has any experience in using a micro-display system, or expose to other virtual environment within the last month.
- 1.2.6. Ask the participant to take 5 minutes rest for the purpose of calm down.

1.3. Perform Pre-task Vision Test

- 1.3.1 Test the participant's vision using the OPTEC 2000 vision tester.

1.4. Apparatus Setting

- 1.4.1. Measure and record the inter-pupillary distance (IPD) of the participant.
- 1.4.2. Clean the forehead and chin rest by alcohol wipe.
- 1.4.3. Coarsely adjust the micro-display system to the suitable IPD value and set the lens focus to infinity.
- 1.4.4. Turn on the micro-display.
- 1.4.5. Ask the participant to place his / her chin and forehead at the chin and forehead rest.
- 1.4.6. Ask the participant to adjust the seat in order to sit comfortably.
- 1.4.7. Finely adjust the micro-display system for the left eye for optimum viewing.
- 1.4.8. Ask the participant to open the left eye and close the right eye.
- 1.4.9. Ask the participant if he / she can see a sharp image. If a sharp image cannot be seen, return to 1.4.7.
- 1.4.10. Finely adjust the micro-display system for the right eye for optimum viewing.
- 1.4.11. Ask the participant to open the right eye and close the left eye.
- 1.4.12. Ask the participant if he / she can see a sharp image. If a sharp image cannot be seen, return to 1.4.10.
- 1.4.13. Ask the participant to leave the seat.
- 1.4.14. Fix the position of the adjusted micro-display system and perform trial test on the motor system operation of the system.
- 1.4.15. Record the customized setting for the participant.

1.4.16. Set the lens focus to 200cm.

2. Practice

2.1. Procedure

2.1.1. Ask the participant to place the forehead and chin at the forehead and chin rest.

2.1.2. Ask the participant to use both eyes and see if he / she can see a sharp image. If a sharp image cannot be seen, return to 1.4.7.

2.1.3. Explain to the participant the meaning and concept of single image, double images and single stereoscopic image.

2.1.4. Instruct the participant how to use the response button of the computerized response system.

2.1.5. Practice with the participant in using the response button.

2.2. Post-practice work

2.2.1. Ask the participant to fill in a Pre-task Simulator Sickness Questionnaire (SSQ) (Remark: This data was not studied in this thesis)

3. Experiment Rundown

3.1. Initial Setting

3.1.1. Place a notice outside the laboratory (the experiment venue) to prohibit any entry of other people.

3.1.2. Set the pre-arranged lens focus to 40cm and 200cm, depends on the experiment condition going to be conducted.

3.1.3. Turn off all the lighting in the laboratory.

3.1.4. Ensure all other luminous objects are covered.

3.1.5. Ensure the computerized response system is ready.

3.2. Experimental Procedure

3.2.1. The participant first takes a rest in the experiment venue for 5 minutes.

3.2.2. Ask and record the participant's eye tiredness rating (Remark: This data was not studied in this thesis).

3.2.3. Turn on the micro-display system and display biocular images.

3.2.4. Inform the participant which virtual object he / she should fixate at.

3.2.5. Ensure the participant can form a sharp single image.

3.2.6. Display binocular images after a non-constant delay of 3-20 seconds.

3.2.7. After the participant indicates the perception of a single stereoscopic image through the response button for 10 seconds, display biocular images after a non-constant delay of 3-20 seconds.

3.2.8. After the participant indicates the perception of a single image through the response button for 10 seconds, this forms a complete dependent trial of single image formation data measurement.

3.2.9. Repeat 3.2.3 to 3.2.8. four more times. This is a complete condition of the experiment.

3.2.10. Ask and record the participant's eye tiredness rating (Remark: This data was not studied in this thesis).

3.2.11. Ask the participant to rest 5 minutes in complete darkness.

3.2.12. Repeat 3.2.2 to 3.2.11 until all 12 conditions (i.e. the 3 repeated blocks) are completed.

3.3. Post Experimental Procedure

3.3.1. Ask the participant to fill a Post-task Simulator Sickness Questionnaire (SSQ) (Remark: This data was not studied in this thesis)

3.3.2. This is a complete session of the experiment.