Effects of Head and Hand Movements Lags on Task Performance in a Virtual Environment

BY

CHUNG KA MAN, BEng.

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AUTHORISATION

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To Rachel

Effects of Head and Hand Movements Lags on Task Performance in a Virtual Environment

ABSTRACT

Virtual Reality (VR) systems enable users to interact with computer-generated objects in a natural manner. However, inevitable time lags occur when a Virtual Reality system responds to dynamic head or hand movements of a user. Many studies have reported the time lag problems with Virtual Reality systems but studies on the combined effects of head and hand movement-related lags are few. The purposes of this research are to determine the effects of (i) head movement-related lags, (ii) hand movement-related lags, and (iii) combined head and hand movement-related lags on manual task performance. Both discrete and continuous manual tasks have been investigated and the mechanisms responsible for the degraded performance with lags have also been studied and identified. In addition, quantitative models to predict the task performance in the presence of hand movement-related lags and combined hand and head movement-related lags are presented.

Four experiments were conducted. With discrete manual tasks, both additional head movement-related lags ($\geq$ 110ms) and hand movement-related lags ($\geq$ 55ms) significantly increased the task completion times. Effects of hand movement-related lags were found to be significantly greater than the effects of head movement-related lags of the same magnitudes. With continuous manual tracking tasks, tracking errors increased with increasing hand movement-related lags but not with increasing head movement-related lags (up to 440ms). It was found that the effects of hand movement-related lags had significant interactions with the effects of target width but not with target distance. This contradicts some previous findings. A model explaining this interaction phenomenon has been developed. With the presence of head movement-related lags, the opposite was found. That is, the effects of head movement-related lags had significant interactions with the effects of target distance but not with target width. The interaction results indicate that, in the presence of lags, the effect of target width (W) and distance (D) should not be analyzed as a single effect of 'Index-of-Difficulty, ID' ($ID = \log_2 2D/W$). This is a new finding. With a constant lag, discrete target-directed hand movement times were found to be consistent with Fitts' laws ($R^2 > 0.8$). Regression models were developed to predict the effects of hand movement-related lags ($R^2 > 0.9$) and the combined effects of hand and head movement-related lags ($R^2 > 0.9$). The implications of the effects of lags are discussed.

CHAPTER 1 Introduction

1.1 Background

Computer technologies have been advancing at a stunning speed; people want a more user friendly and interactive computer interfaces. Such an interface should enable a user to interact with computer generated environments through his/her sense of sight, hearing, and touch. A Virtual Reality system, seems to be the best solution to meet this demand. A typical Virtual Reality (VR) system consists of a Head Mounted display (HMD), a 3D tracking system, and a computer. This system allows the users to visually and physically interact with a computer-generated 3D world in a natural way. Auditory and tactile interfaces can be added. This thesis will focus on the visual-motor interaction with a VR system. This section will discuss what is a Virtual Reality system and its applications.

1.1.1 What is a Virtual Reality system?

"Virtual Reality is a way for humans to visualize, manipulate and interact with computers and extremely complex data." (Aukstakalnis and Blatner, 1992). The visualization part refers to the computer generating visual, auditory or other sensual outputs to the user of a world within the computer. This world may be a CAD model, or a scientific simulation. The user can interact with the world and directly manipulate objects within the world.

One typical example was reported by So (1996) (Figure 1-1). Immersive Virtual Reality system presented computer-generated images stereoscopically in three dimensions. A user can change his viewpoint by moving his head and can control the orientation of a computer-generated hand image (virtual hand) by moving his hand. In this example, there were basically three components, a Head Mounted display (HMD), a 3D tracking device, and a computer. The usability of the Virtual Reality system was driven by the improvement of the technology of these three basic components, the advanced technology both enabled the use of VR systems, and improved its feasibility.

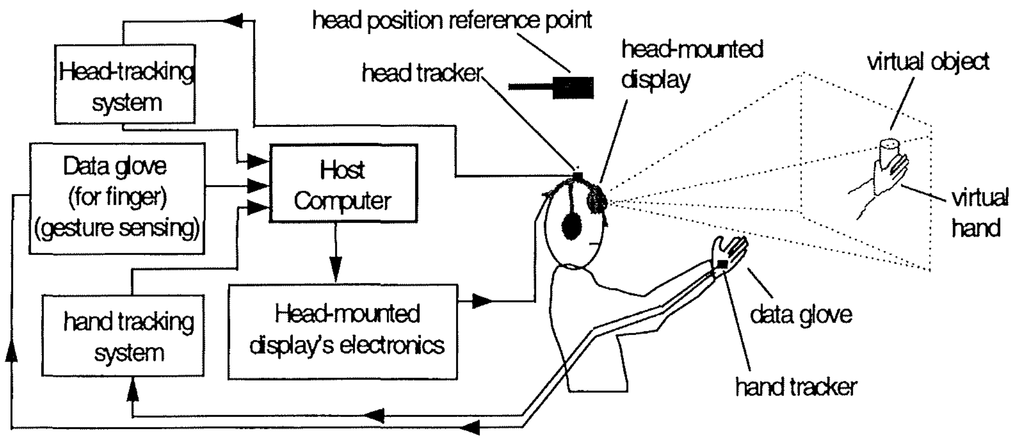

Figure 1-1: A typical virtual reality system showing a hand manipulation task

1.1.2 Applications of Virtual Reality systems

The application of Virtual reality systems covered a wide range, for example, virtual prototyping, design evaluation, ergonomics studies, construction engineering, reconstruction of historical building, manufacturing planning, surgery, training, computer aided design (CAD), architecture, entertainment and even space projects. They can be grouped into four main application areas, design, training, telematics control and entertainment.

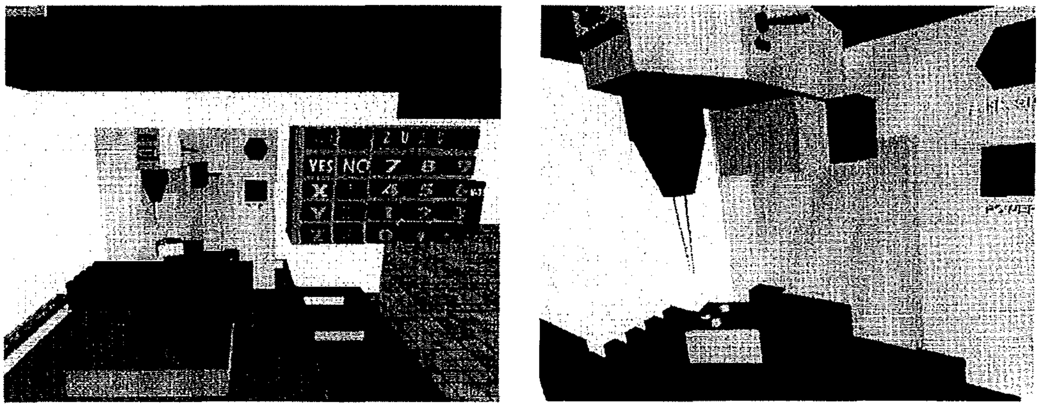

Figure 1-2: Virtual Reality CNC milling machine (Virtual Training)

Training is one of the most popular applications of VR systems. Using the capability of simulating a scene and responses to some actions, the VR training application allows a low risk level and great efficiency. One example was the VR CNC milling machine (Lin *et al.*, 1996). The operations and the training sessions of the machine were performed inside the virtual world thus ensuring maximum level of safety during the training section.

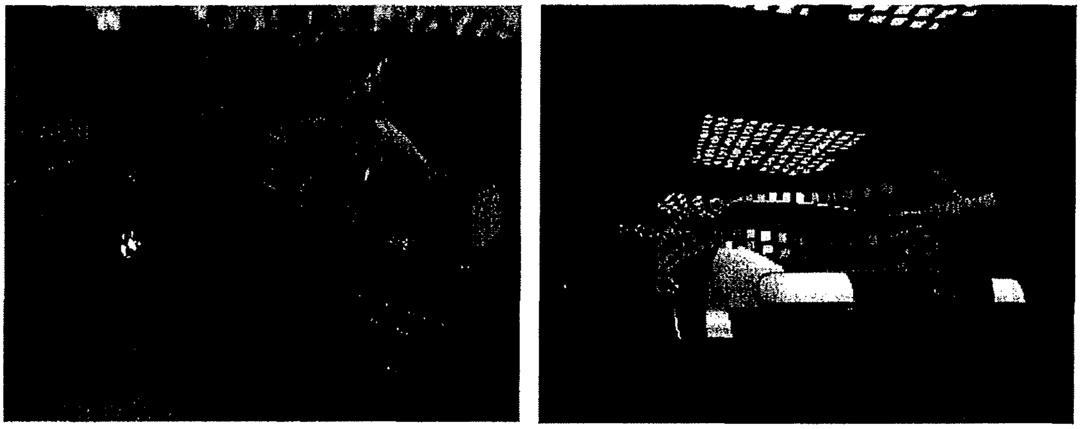

Figure 1-3: Driving simulation and digital prototyping in car industries

Another popular example is driving simulation. It is widely used in many driving institutions, where VR systems may simulate the road environment. By using VR, the students can be taught to effectively respond to different accident situations.

Bullinger and Fischer (1998) reported the use of VR systems in digital prototyping, to visualize products in both design and marketing aspects. The use of digital prototyping greatly improved the time needed to create and modify the prototyping model. It directly reduced the cost of development, and also the development cycle, which increased the competitiveness in this fast changing world, with very short product life cycle.

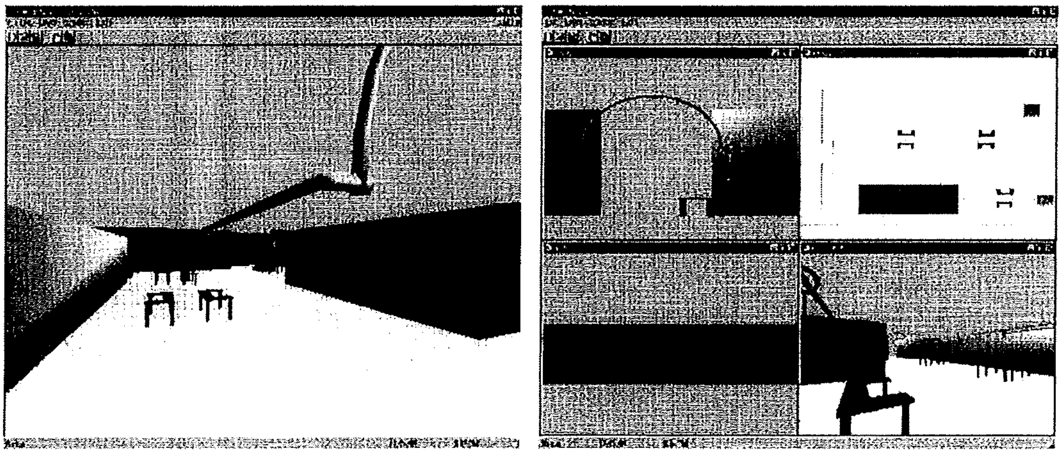

Figure 1-4: Snapshots of the Virtual Reality Facility Layout Design system (Chung *et al.* 1998)

Other than product design, VR systems may also be applied in manufacturing planning and floor plan design. In our previous study a Virtual Reality facility layout design system was developed (Chung *et al.* 1998). Using this system, we can design the facility layout of the manufacturing plan, to overview, visualize and evaluate the effectiveness of the layout design. This type of tool can avoid costly mistakes during the design process, since the designer can visualize the mistakes before they are actually made.

VR systems also have an important role in the telematics applications. For example, the applications in tele-operations, VR systems are effective in accessing an the objects remotely. Some examples are tele-surgery, space project, and robotics control.

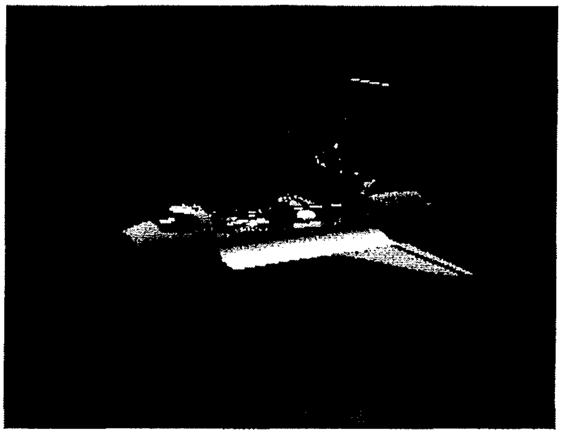

Figure 1-5: Space project using Virtual Reality

A great area of application of VR systems is entertainment, from 3D movies to gaming. Recently, most games have been using real-time rendered 3D graphics, some of them even supporting head-mounted display during the game playing.

Virtual Reality system will remain very useful in the future. Some applications are already on the market but some still face many limitations. However, with the rapid improvement in technology, more and more VR applications may come true and used in real application areas. The studies on how to enhance the usability of the VR systems were essential for the future development of VR systems. A useful reference about Virtual Reality system is Toni Emerson's "On The Net resource in Virtual Reality" web site: http://www.hitl.washington.edu/projects/knowledge_base/onthenet.html

1.2 Problem statement

"Hey! Why do the virtual scenes surrounding me appear to be floating up and down?". Similar expressions have been the most popular question from Virtual Reality (VR) systems users. The 'floating' effects are caused by the time lags within a VR system. Time lag occurs when a Virtual Reality system responds to head and hand movements. It is one of the greatest problems in VR and it also affects the task performance (Kenyon and Afenya, 1995). Time lags have been shown to degrade many task performances presented in a Virtual Reality system. Examples from the literature include: flight simulation (Woltkamp and Ramhandran, 1988); a simple 'pick and place' task (Kozak et al., 1993, Kawara *et al.*, 1996 and Kenyon and Afenya, 1995); manual tracking task (Ellis *et al.*, 1997a,b); head tracking task (So and Griffin, 1992); and manual discrete task (Ware *et al.,* 1994a,b).

Although computer technologies have been advancing fast, the most up-to-date VR systems still inevitably suffer from time lags. As reported by Ellis *et al.* (1997a,b) at NASA AMES the immersive VR system was still suffering from 80 ms system lag. The problem of time lag is hence very important barrier for the usability of VR systems. The studies on the effects of lag in VR systems were crucial.

Effects of lag was a very important factor, that affected the task performance in Virtual Environment (VE), so how could this affect the human? Although the effects of time lags on various tasks have been studied extensively, all studies had put their focus on the effects of lag only. What is needed is a qualitative model to describe the mechanisms by which time lags affect visual task performance and a quantitative model to predict the task performance degradation in VE.

Some important tasks, which could be performed frequently, have not enough attention in research, for example, manual discrete tasks. A comprehensive overview of the effects of lags in VE still cannot be formulated, due to the deficiency of the studies of these basic and fundamental tasks.

The application of VR systems has becoming more complex; the hand movement related lag and head movement related lag sometimes might be different. There is a lack of studies on the effects of the combined hand and head-related lag and the interaction between these two lags.

In order to fill in these gaps and provide a comprehensive knowledge of how time lags affects task performance, predictive models of task performance and mechanisms behind them, a preliminary experiment and three experiments were designed and conducted in this study.

1.3 Purpose of research

The purposes of this thesis is to provide a comprehensive knowledge of the effects of time lags on both discrete and continuous manual tasks performed in a Virtual Environment (VE). This includes the understanding of the mechanism through which time lag could affect the manual task performance. Specifically, the objectives for the thesis are to:

(i) determine the effects of head-related lags on task performance;

(ii) determine the effects of hand-related lags on task performance;

(iii) determine the effects of combined lags on task performance;

(iv) study and identify the mechanisms causing degraded performance; and

(v) study and propose a quantitative model to predict discrete manual task performance in the presence of lags.

1.4 Organization of the thesis

The organization of the thesis is summarized as follows:

Chapter 1 - Introduces the architecture of a typical Virtual Reality (VR) system, applications of VR systems, and associated time lag problems.

Chapter 2 - A review of literature on the effects of lags in Virtual Reality systems. The objective is to identify the possible areas that will require future studies.

Chapter 3 - A review of literature on the visual-motor control theories and models concerning the effects of delayed visual feedback. Possible applications of these models on a Virtual Reality system are discussed.

Chapter 4 - An overview of the experiments, including the description of the methodology, subject, apparatus and the techniques used in the analysis of the experiment.

Chapter 5 - An experiment conducted to investigate the effects of practice on manual performance. (EP_D)

Chapter 6 - An experiment conducted to investigate the effects of hand related lag on discrete manual performance (EHA_D).

Chapter 7 - An experiment conducted to investigate the effects of combined lag on discrete manual performance (EHA&HE_D).

Chapter 8 - An experiment conducted to investigate the effects of combined lag on continuous manual performance (EHA&HE_C).

Chapter 9 - The chapter includes (i) a summary of the major findings in the four experiments, (ii) a design guideline of VR systems, (iii) a qualitative model to describe the mechanism by which time lags affects manual task performance, and (iv) a quantitative model to predict performance degradation in discrete manual task. Recommendations for further experiments are also presented. A summary of the flow of the thesis is illustrated in Figure 4-1, (Chapter 4).

Chapter 2 Effects of time Lags in Virtual Reality Systems (A Literature Review)

2.1 Introduction

Time lag in Virtual Reality has been reported as one of the most domiant problems affecting task performance in Virtual Environment. In this chapter, the definition of time lag in a Virtual Reality system will be discussed. The previous literature on the effects of time lag in virtual environment, and the searches of the possible research gaps will also be discussed in this chapter.

2.2 Definition of time lags in a Virtual Reality system

2.2.1 General definition

Time lag in Virtual Reality is defined as the time between the moment when a tracker or a user first moves and the time at which the most updated image is displayed on the Head Mounted Display (HMD) (Bryson and Fisher, 1990 and Taylor *et al.*, 1996).

2.2.2 Flow of information in a typical VR system

A typical Virtual Reality system consists of a HMD, or a surround projection system (e.g., CAVE™), a tracking system, and a graphical computer. When the user moves his hand, the hand position tracking system detects the updated position and orientation, this information is then used to render and display an updated image on the Virtual Reality display.

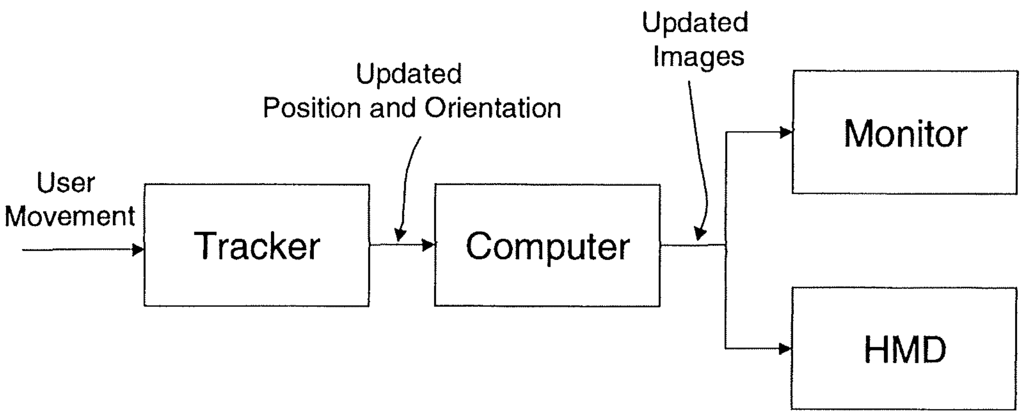

Figure 2-1: Block Diagram of the information flow of a typical VR system

A simple block diagram illustrating the flow of information within a typical Virtual Reality system is shown in Figure 2-1. It is not difficult to appreciate that the flow of information and the process of each block takes time. Therefore, when the users move their hands, they cannot see the movement of their virtual hands immediately. A more detailed explanation of the operations performed in each block is shown in Figure 2-2 below.

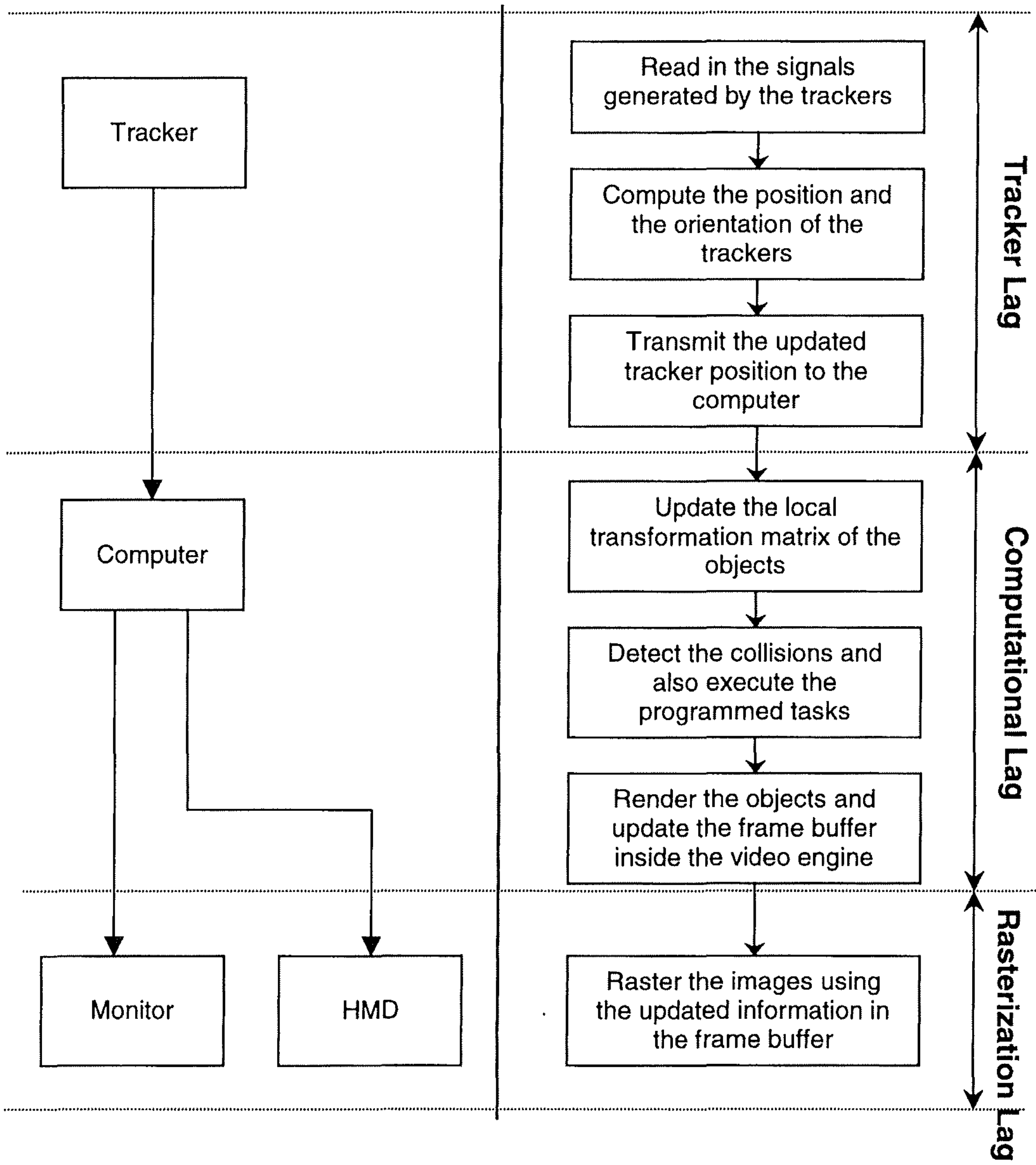

Figure 2-2: The detailed operation of each block that could introduce time lag

The three blocks, each contributed to specific types of lag: tracker lag, computational lag, and rasterization lag. These are the three major sources of lags in a Virtual Reality system. As reported by So (1995), and the summary table of the recent studies in table 2-1, the time lag in current Virtual Reality systems ranges from 16.7 to 150 ms.

2.2.3 Types of lag

Different types of lags exist in a VR system. This literature review will focus on two major types of lags, head-related lag, and hand-related lag.

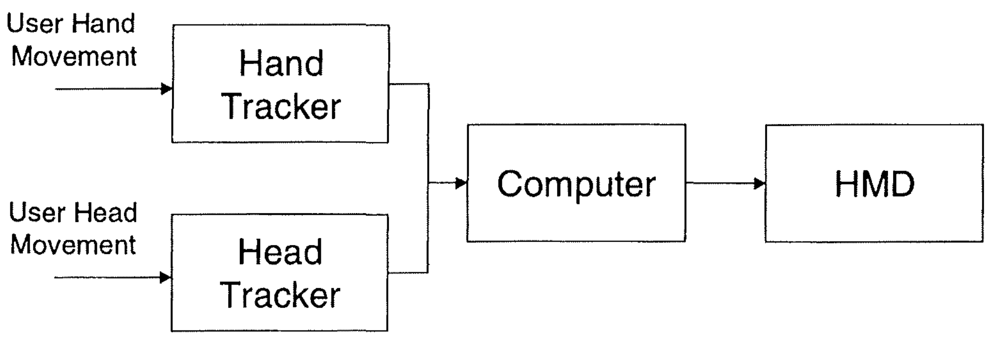

Figure 2-3: Different types of lags, Hand and Head-related lags

For the hand-related lag, it is associated with the hand movement and the display of hand. In other words, it is the time between the moment when the hand first moves and the time at which the most updated virtual hand image is displayed on the virtual display. Similarly, head-related lag is associated with the head movement and the display of the updated view.

2.3 Problems and Solutions of time lag in Virtual Reality system

Although computer technologies are advancing rapidly and both the cost and performance have improved dramatically, virtual environments still suffer from lag problems. As reported by Levine *et al.* (1996), their driving simulator suffered from a tradeoff between the quality of the graphics and their update speed. They suggested that lag is an important factor for driving performance and immersion. All the studies listed in the table 2-1 reported lag-induced performance degradation inside the Virtual Environment. Kenyon and Afenyon (1995) further stated that time lag in a VE is one of the most dominant factors that degrades task performance. Other than the task performance degradation, time lag could also induced Cybersickness (Dizio and Lackner, 1997; Hash and Stanney, 1995; Homola *et al.*, 1997; Strauss, 1995). Homola *et al.* (1997) suggested that the nausea symptoms associated with Cybersickness is the result of the malfunction of the vestibule-ocular reflex (VOR) due to the lag in a VR system. Time lag in VE is creating many problems including performance degradation and also Cybersickness.

In order to tackle the problem of lag, many solutions have been suggested. The solutions can be categorized into two main streams (i) improvement of the computational speed, and (ii) time lag compensation. Lag compensation methods have been proposed by many studies (Keyger and Maybeck, 1998 & 1997; Olano *et al.*, 1995; Azuma and Bishop, 1995; So and Griffin, 1996, 1992). These methods treat the human operator and the VR system as one delay element (see Figure 2-4). A predictive filter is, therefore, used to predict the movement of the operator for a time interval equivalent to the duration of the delay element. If the prediction is perfect, the updated images will be free of lag. Many compensation algorithms have been proposed and shown to improve task performance in VR systems with lags. However, the reliability of these algorithms is still questionable because of the lack of understanding on how time lag affects the behavior of the human operators.

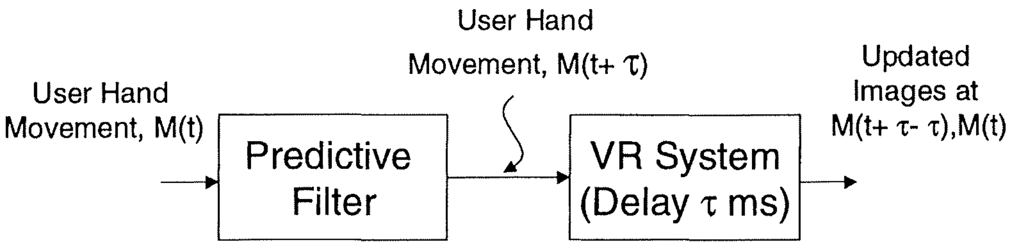

Figure 2-4: Lag compensation in VR system

The most direct approach to reduce time lag is to improve the computational speed, since it is the main source of time lag in Virtual Environment. Banks (1997) suggested the use of multiple graphics engines to render images corresponding to the viewpoints. Schaufler and Sturzlinger (1996) implemented a memory cache for three dimensional images so as to reduce the rendering load of the hardware. Both approaches reported a reduction in latency of their VR systems. However, due to the growing demand for more and more complex Virtual Reality applications, the improvement in computer speed cannot catch up with the demands of the applications. As reported by Ellis *et al.* (1997b), the immersive VR system in NASA AMES still suffered from a 80ms system lag, even with simple graphics. The problems of lag is still one of the most dominant problems with Virtual Reality systems.

2.4 Previous studies on the effect of lags in Virtual Reality systems

Problems of lags have caused serious performance degradation in VEs. Many studies have examined this problem. (e.g., with manual control task: Ware *et al.* 1994a; Richard *et al.* 1996; Ellis *et al.* 1997a, 1997b ; with head control task: So and Griffin, 1995c). The purpose of these studies was to determine how time lag could affect the task performance. Time lag was manipulated as one of the variables in these studies. A summary of the studies is shown in Table 2-1. The research was mainly divided into two different tasks: manual and head control as shown in Figure 2-5.

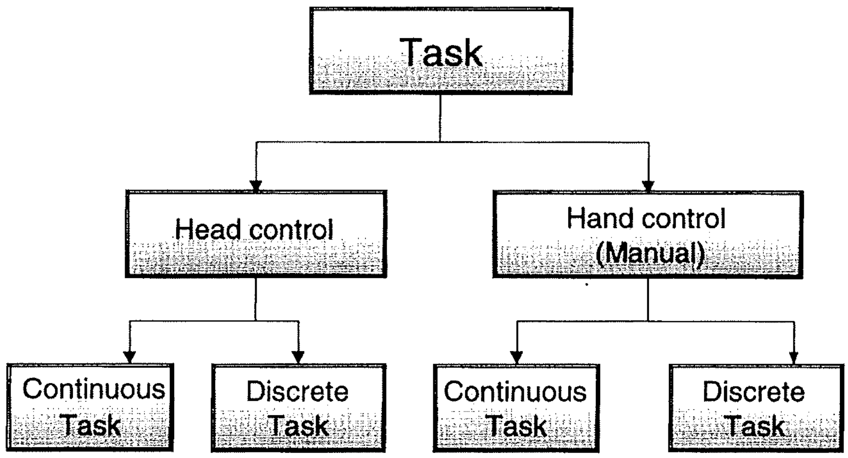

Figure 2-5: Overview diagram of the research area of previous studies

There are two main types of tasks: head control and hand control (manual) task in Virtual Reality system. Head control tasks are frequently performed during a flight simulation session in which the aircraft pilots are required to track a moving target using a head-slaved aiming cross presented on their helmets. Manual control tasks are the most common tasks that we perform daily. Different types of manual tasks are performed every day, for example, turning on a lamp, selecting a floor in the lift, cutting paper following a line, or driving on a road. Tasks like turning on a lamp, or pressing a floor button in the lift, are categorized as discrete tasks, since they only require simple ballistic hand movements. The cutting and driving tasks require continuous feedbacks and adjustments, these tasks are categorized as continuous tasks.

So and Griffin (1992, 1995a,b and 1996) conducted several experiments concerning the effects of lag in head-related continuous tracking tasks. In their studies, subjects were asked to track a target using a helmet-pointing system in the presence of imposed time lags (time lags in addition to the base system lag). The head-related time lags used in these experiments were 0, 40, 80, 120, 160ms. They reported that the head tracking performance would degrade significantly for imposed time lags of 40 ms or more on top of a 40ms base lag.

Ellis *et al.* (1997a,b) conducted a study investigating the effects of lag on continuous task performance. Subjects were asked to pass a virtual ring through a pre-determined path while avoiding contact between the ring and the path. They found that the increase of latency by delaying the rendering time could increase the tracking errors. The imposed time lags in this study were 50, 100, 200, 300 and 500ms. These time lags were imposed by manipulating the rendering latency, in the other words, both hand and head related lags were kept on the same level. In the same year, Bryson (1993) also conducted a manual tracking task study investigating the effects of imposed time lag. He found that the tracking errors were linearly related to the delay time.

Besides, manual continuous tasks, the effects of lag on discrete manual task performance within a virtual environment has also been studied (Ware and Balakrishnan, 1994b). They also reported that task performance is degraded with the increasing lags. They further modeled the effect on manual movement time (MT) with a modified Fitts' Law. The lags and index of difficulties (ID) have a multiplicative effect on the movement time (i.e. MT = A+B*ID+C*(ID)*(Lag)). This finding is consistent with that of Hoffman (1992), who investigated the effects of hand related lag on discrete tracking task in a real world environment.

2.5 Lessons learnt from the literature review

The literature reviews indicates that there are few studies on hand-related lag in the hand movement related discrete task. Although Ware *et al.* (1994a,b) studied the effect of hand lag on discrete task using 3D mouse, the effects are still unclear in the immersive system with the virtual hand as the control; there could be many differences between the task using 3D mouse and a CyberGlove.

Ellis *et al.* (1997a,b) studied the effects of frame rate in a manual continuous tracking task, however, the interaction between the head and hand-related lags were not studied. This interaction effect is important for the design of VR applications in which an optimal balance between the duration of hand and head-related lags are needed.

This literature review identifies a gap in the current knowledge about the effects of lags in VE. The modelling of the effects of lags in VR system has received little attention. Although some studies tried to model the effects of lag using modified Fitts' Law equations, the mechanism of how human beings behavior could be affected by lags were not studied. The understanding of this mechanism can enable designers and engineers to make enhancements in the future Virtual Reality systems.

Reference	System				Manipulated Lag Durations	Task Performanced	Reported performance degradation with lags
	Display	Control System	Tracking System	Graphics Computer			
Arthur, K.W. Booth, K.S. Ware, C. (1993)	Desktop Monitor (StereoGraphics Crystal Eyes stereo system)	Mouse	Head position: ADL-1 mechanical tracker	Silicon Graphics IRIS workstation	Frame rate: 30Hz, 15Hz, 10Hz Lag: 0, 1, 2, 3, 4 frame intervals Base Lag: 33ms	Find out the distinguished leaf belongs to one of the two trees	**Yes** Lag: 50ms -> 550ms Performance: 3150ms -> 4200ms
Ware, C. Balakrishnan, R. (1994b)	Desktop Monitor (StereoGraphics Crystal Eyes stereo system)	Polhemus Isotrak sensor with a button into a Mouse	Head pos: Logitech head tracker Hand pos: Polhemus Isotrak sensor	Silicon Graphics IRIS Crimson/VGX workstation	Frame rate: 16.7ms -> 1000ms Hand Lag: 95ms -> 812ms Base Lag: 16.7ms	Use the tracker to move a cursor on a target and press the mouse button	**Yes** Frame interval: 67ms -> 1500 ms Hand Lag: 95ms -> 812ms Performance: 2500ms -> 7400ms
Richard, P. Birebent, G. Coiffet, P. Burdea, G. Gomez, D. Langrana, N. (1996)	Desktop Monitor (LCD shutter glasses)	DataGlove (VPL, 1987)	Hand Pos: Polhemus tracker Force Feedback: Rutgers Master	Data Glove & information of the virtual object: Sun 4 Rendering: HP 755-48Z	Frame rate: 35, 71, 142, 333, 500, 1000ms Base Lag: 28ms	Track a moving target and grab it as quickly as possible (Remarks: 84 subjects were participated in this experiment, 42 male, 42 female)	**Yes** Frame interval: 35ms -> 1000ms Performance: 990ms -> 6960ms

Table 2-1: Summary table of the previous studies on the effect of lag in VE (Cont.)

Reference	System				Manipulated Lag Durations	Task Performanced	Reported performance degradation with lags
	Display	Control System	Tracking System	Graphics Computer			
Kawara, T. Ohmi, M. Yoshizawa, T. (1996)	Head mounted display (HMD-RB2, VPL Research) FOV: 110° X 77°	DataGlove (VPL Research)	Head position: Polhemus Tracker Hand Position: Polhemus Tracker	Silicon Graphics Indigo2 extreme	Head Lag: 0, 300, 500ms Hand Lag: 0, 300, 500ms	Grasp a 6 cm in diameter, 10 cm high cylinder and move it from the right side of a table to left side	**Yes** Head Mode: Lag: 0ms -> 500ms Performance: 100% -> 135% Hand Mode: Lag: 0ms -> 500ms Performance 100% -> 120%
Watson, B. Spaulding, V. Walker, N. Ribarsky, W. (1997)	Head Mounted Display (VR4, Virtual researches) FOV: 48° X 36°	Plasstic mouse	Head Pos: Polhemus Isotrak 3D Tracker	Silicon Graphics IRIS Crimson/VGX workstation	Frame time: 100ms, 50ms Lag: 100ms frame time: 285ms 50ms frame time: 235ms Base Lag: 213ms	Visually tracked on moving target object grabbed it, and place it on a pedestal within a certain tolerance	**Yes** Lag: 235ms -> 285ms Performance: 4300ms -> 5020ms
Ellis, S.R. Breant, F. Menges, B. Jacoby, R. Adelstein, B.D. (1997a,c)	Haploscope 1.5 in. 1000 line, monochrome	Polhemus Fastrak Sensor	Head Pos: Polhemus Fastrak sensor Hand Pos: Polhemus Fastrak sensor	Silicon Graphics (4D/440IG2)	Lag: 50, 100, 200, 300, 500ms Base Lag: 32ms	Pass a toruse over a path, to avoid the contact between the toruse and the path	**Yes** Lag: 50ms -> 500ms Performance: 13 secs -> 23 secs

Table 2-1: Summary table of the previous studies on the effect of lag in VE (Cont.)

Reference	System				Manipulated Lag Durations	Task Performanced	Reported performance degradation with lags
	Display	Control System	Tracking System	Graphics Computer			
Ellis, S.R. Dorighi, B.M. Menges, B.D. Jacoby, R.H. (1997b)	HMD (VR4, Virtual Reseaches)	Polhemus Fastrak Sensor	Hand Pos: Polhemus Fastrak sensor Head Pos: Polhemus Fastrak sensor	Silicon Graphics (Skywriter with RE-1)	Lag: 80, 130, 230, 380, 480ms Frame rate: 6, 12, 20Hz Base Lag: 80ms	Keep a tetrahedron centered in a virtual wire-frame cube	**Yes** Frame interval: 80ms -> 480ms Performance: r.m.s. Error ~0.1 -> ~0.25 A. Cooper-Harper ~3 -> ~5
Rogers, S.P. Spiker, V.A. Fischer, S,C. (1997)	IMTEC monochrome monitor (Model 1455N)	Polhemus Insidetrak Sensor mounted on a plastic helmet	Head Pos: Polhemus Insidetrak Sensor	IBM 386 computer	Imposed Lag: 0, 20, 40, 60, 80,100, 120 ms Base Lag: 20ms	Move the cursor (head-controlled) from its original location to the stationary target and hod it there for 120ms	**Yes** Lag: 20ms -> 140ms Performance: 1790ms -> 2450ms
So, R.H.Y. Griffin M.J.	Helmet-mounted display model SD/HMD-001 FOV: 17° X 17°	Helmet pointing system, Ferranti SPASYN system type 101	Head Pos: SPASYN system		Imposed Lag: 0, 40, 80, 120, 160ms Base Lag: 40ms	Move their heads to track the target with an open-cross reticle displayed at the center of the HMD	**Yes** Lag: 40ms -> 200ms Performance: At the fastest velocity: 0% inc. in error -> 50% increase

Table 2-1: Summary table of the previous studies on the effect of lag in VE

Chapter 3 Visual-Motor Control theories (A Literature Review)

3.1 Introduction

When performing common tasks like opening a door, picking up a pair of glasses, switching on a TV, we rely mostly on the visual information obtained from our sensory mechanisms. Tasks involving visual information and followed by motor movement have been referred to as 'visual-motor control tasks' and they have been studied for many years. Many theories of how humans could use these sensory information to perform the motor tasks have been developed.

Visual-motor control tasks can be divided into many categories, for example, manual control task, head control task, and leg control task (walking). These tasks can also be further divided into continuous task, and discrete task. Discrete task involves a single reaching movement to 'hit' a stationary target, such as, reaching for a cup, or pushing a button (Glencross and Barrett, 1988). Whereas, the continuous task involves trail-to-trail tracking movements, such as driving a car, tracking a moving target. In this chapter we are concerned with two main categories of manual control: (i) continuous manual tracking task, and (ii) discrete manual task. The reasons for this narrow selection are two-fold: first, the manual tasks are the main concerns in this study, second, it is also one of the most popular tasks in a Virtual Environment (VE).

Knowledge of human behavior in a visual-motor task can help our understanding of how a user will behave in a VE. Some studies have also reported visual-motor behavior in the presence of delayed visual feedback. These studies can greatly assist the development of a model of the effects of lag in a Virtual Reality system.

This chapter will discuss the reviewed literature about visual-motor tasks and the effects of delayed visual feedback. Based on this past knowledge, we can further investigate the mechanism of how humans are affected in a Virtual Environment with lags.

3.2 Visual-motor control models

3.2.1 Visual-motor control models for continuous manual tracking tasks

People perform visual-motor tasks based on several sources of sensory information (e.g. proprioceptive, audible, visual, touch, etc...). However, the most important information is proprioceptive and visual information. Using the visual information, they can pre-program the initiation and control of future movements (Miall *et al.*, 1995). The proprioceptive information informs about the position, location, orientation, and movement of the body, by providing the brain with information about the status and activity of muscles and joints.

3.2.1.1 *Movement of the index finger*

The mechanisms for movement in different types of tasks are very complex. We will use the control of an index finger as an example to illustrate the mechanism of how human performs visual motor tasks.

Movement of the index finger is a very simple and common task. In this simple task, we rely on visual information to estimate the error or difference in positions between the index finger and the target. This information is then processed in cortex through a series of mechanisms. In order to minimize the error, a set of movements are performed. The error signal and movement create a visual loop that is involved in the performance of a motor task (moving an index finger). The proprioceptive input is similar to the visual loop in that proprioceptive signals are conveyed to the brain, which follows a set of routines to process the visual and proprioceptive information together and then issue commands to perform the best action.

Beuter *et al.* (1989) reported on the control mechanism to control index finger movement (Figure 3-1). Afferent signals from the retina (visual) and proprioceptors (proprioceptive) are conveying to the cortex via separate nuclei of the thalamus and basal ganglia. The first site of interaction of this afferent information for the task is in association with areas of the cortex (i.e. the parieto-occipital lobes). The movement information is sent to the spinal cord and finger through the corticospinal and rubrospinal tracts. The feedback information from vision and limb movements (i.e. spinocerebellar tract) is modulated by cerebellum.

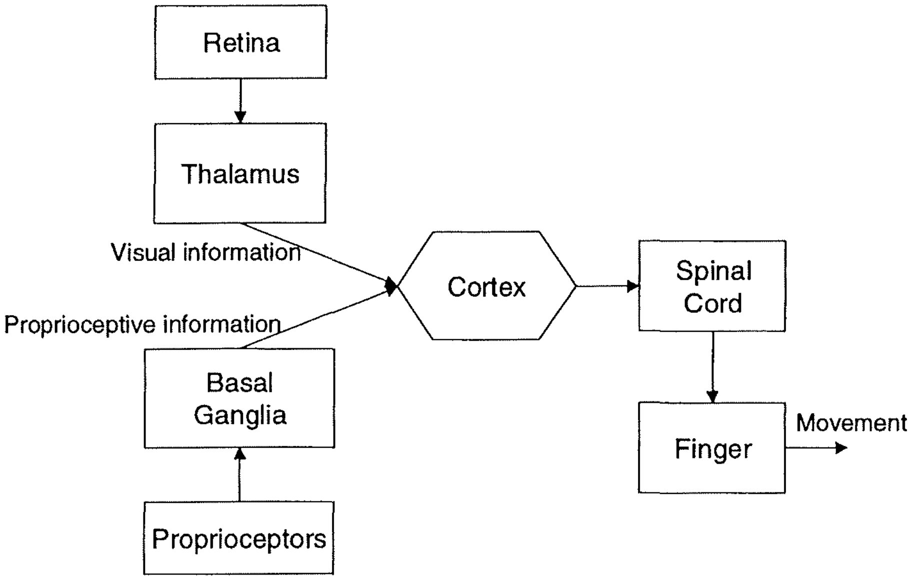

Figure 3-1: Neuroanatomical moel of multiple feedback loop (Beuter *et al.,* 1989)

The above Neuroanatomical model reported by Beuter *et al.* (1989), gives us an understanding of how the afferenet signals are transmitted to the brain and how the motion information is sent to the motor control. However, from the past literature the interaction between the proprioceptive and visual information is not clear. How this information is processed in our brain, and which part of the brain is used are still unsolved questions. Miall *et al.* (1995) reported that humans are able to learn and pre-program their movement on the basis of visual cues and proprioceptive information. The research shows that the visual and proprioceptive information are working together to generate or develop a motor program for a control movement.

3.2.2 Visual-motor control models for discrete manual control tasks

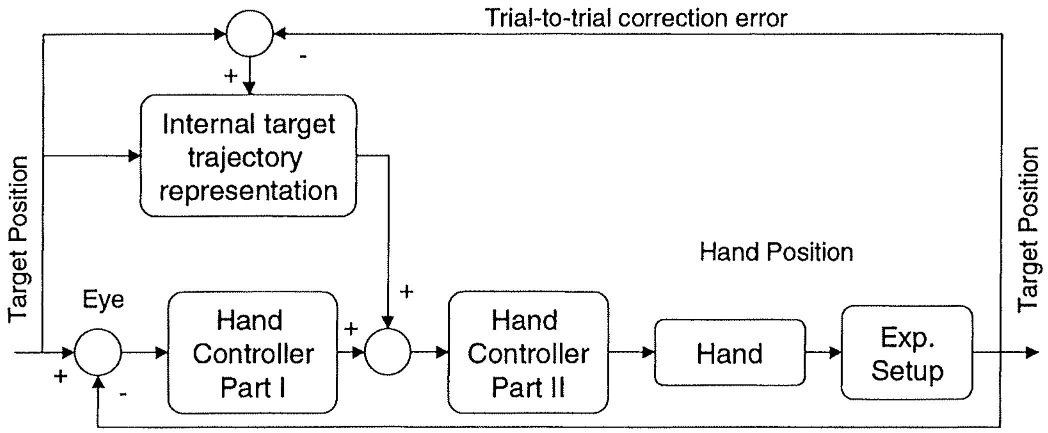

Figure 3-2: Visuo-manual system model (Guédon *et al.*, 1995)

Figure 3-2 shown above is a simplified visuo-manual model was proposed by Guédon *et al.* (1995). The internal target trajectory representation is the place where the motor programs are storing as reported by Miall *et al.* (1995). Knowledge of the hand position and visual cues collected from the proprioceptors and the retina are used in processing and developing a visuo-motor program. The program is in the form of visuo-motor information that allows the user program to adjust each movement as needed (Miall *et al.* 1995).

This internal target trajectory representation stores the visuo-motor information that allows the user to program different types of movement. When the target is predictable, the information developed in the internal target trajectory representation will be activated and the hand movement will rely on predictive control and require less visual information.

When the users are trying to push a button using their index finger, they need to perform two types of movement, (i) a discrete movement, (ii) followed by a set of continuous tracking movement. During the manual discrete movement, since the users were allowed to look at the target position before the movement start, the movement trajectory was developed using the internal target trajectory representation. This internal target trajectory representation provided the movements in feedforward manner. In other words, the movements were activated without feedback, since the visual feedback does not operate on-line and is time costly.

During continuous tracking sessions, the movement of the target trajectory was unpredictable since the changes varied. The hand controller was activated to handle these variable changes,time lag could severely affect the task performance during this session.

3.3 Delayed Visual Feedback

When the visual loop is delayed for some reason, we call this delayed visual feedback. Delayed visual feedback can affect the task performance of manual tasks (Smith, 1962; Beuter *et al.*, 1989; Keran *et al.*, 1994), and it can introduce oscillations and irregular fluctuations during the tracking movement (Beuter *et al.*, 1989 and Glass *et al.*, 1988)

Smith (1962) studied the delayed visual feedback on tracking task intensively. His goal was to develop an electromechanically controlled tracking system from WWII, which suffered from serious delay problems. He found that tracking involves not only a series of equivalent (discrete) responses but a highly organized and precisely coordinated motion pattern made up of at least two main movement components: positioning movement, and transport movement. The transport movement is not discrete but continuous, and it is continuously monitored by visual feedback; when the feedback is delayed, it will become a set of discrete movement. The tracking motions are space-structured relative to target movement, and their accuracy depends on continuous visual feedback signals from the target-cursor display.

Smith (1962) also proposed the use of neurogeometric theory to explain the movement behavior of the motion. He reported that the spatial organization of motion depends on the mode of action of central nervous system neurons stimulated by two spatial points. The temporal organization depends on sensory feedback which monitors a motion pattern. Therefore, the motion requiring almost continuous guidance is most severely affected by time lag.

Studies on the delayed visual feedback in discrete tasks can be found in recent years. Hoffmann (1992) used Fitts' law to predict the effects of lags on target-directed movement times with manually controlled pointers. In

Hoffmann's study, subjects were asked to rotate a knob to move a pen from a starting point to a finishing point. The pen followed the knob movement with four time lags: 30ms, 200ms, 500ms, and 1000ms. Results showed that movement times increased with increasing lags and the increases were found to be proportional to the 'index-of-difficulty (ID)'. That is, the greater the ID, the greater the effects of lag. Hoffmann proposed a modification of Fitts' law to predict the effects of lags on a manually controlled pointer's movement time (*MT*):

$$MT = a + b\,(c + lag)\log_2(2D/W)$$

$$= a + b\,c\log_2(2D/W) + b\,(lag)\log_2(2D/W) \qquad (1)$$

where a, b, c are constants; D is the target distance; W is the target diameter (width); and $\log_2(2D/W)$ is the 'index-of-difficulty'.

In his paper, Hoffmann reported that his model is consistent with the results of two previous studies concerning the effects of lags on discrete manually controlled tasks (Sheridan and Ferell, 1963; and Ferell, 1965).

A similar relationship among movement time, 'index-of-difficulty', and lag were also reported by MacKenzie and Ware (1993) in a study concerning target-directed cursor movements. Targets were presented on a workstation monitor (i.e., a panel-mounted display) and subjects were asked to move a mouse-controlled cursor toward the targets. The results from Hoffmann (1992) and MacKenzie and Ware (1993) suggest that the increase in movement time due to lags depends on the 'index-of-difficulty'. That is, the higher the 'index-of-difficulty', the larger the effects of the lag.

3.4 Lessons learnt from the literature review

From the previous studies concerning the visual-motor control tasks, the following general conclusion can be reached. Motions requiring continuous visual feedback would be most severely affected by time lag. When a lot of visual feedback is required, time lag could greatly degrade task performance. Following this logic and the conclusions of the previous studies, we can establish some guidelines that are useful in the analysis of the effect of lag in virtual environment.

i. The predictable reaching movement in the discrete task can be preprogrammed into the internal target trajectory representation, which requires less visual information, so that this reaching movement is not severely affected by time lag,

ii. In a tracking task, both positioning and transport movement require continuous visual feedback. Therefore time lag can severely affect the task performance in virtual environment,

iii. The results from Hoffmann (1992) and MacKenzie and Ware (1993) suggested an interaction between the 'index-of-difficulty' and the time lag. Therefore, the effects of lag increase with the increase of the 'Index-of-Difficulty, ID'.

Using these guidelines, a better understanding on the effects of lag in virtual environment can be formulated.

CHAPTER 4 Introduction to experiments

4.1 Introduction

From the literature review in Chapter 2, some gaps in knowledge were identified. In order to fill these gaps, a systemic study on the effect of lag was performed. The logical build-up of these experiments will be discussed in this chapter.

4.2 Overview of experimentation

With the knowledge from the literature reviews of the chapter 2, some gaps in the current knowledge was identified:

i. The effect of hand-related visual information lag on hands in a movement discrete task in immersive virtual environment;
ii. The interaction and the combined effects of hand and head-related visual lags on the both continuous and discrete task;
iii. The mechanisms causing degraded performance;
and

In order to fill in these gaps (Table 4-1), and produce a comprehensive study on the effect of lags in virtual environment, four experiments were conducted. They were (i) effects of practice in manual discrete task (EP_D), (ii) effects of hand related lag in manual discrete task (EHA_D), (iii) effects of combined lag for hand and head movements in a target manual discrete task (EHA&HE_D), and (iv) effects of combined lag for hand and head movements in a manual continuous tracking task (EHA&HE_C).

Task Type	Types of Lag		
	Head	**Hand**	**Combined**
Discrete	Few	Few (EHA_D)	Scarce (EHA&HE_D)
Continuous	Many	Some	Scarce (EHA&HE_C)

Table 4-1: Overview of the current knowledge

4.2.1 Effects of practices on discrete manual performance (EP_D)

The goal of this experiment was to study the effects of practice in a manual discrete task. The independent variables studied in this experiment were (i) practices and (ii) target distance.

4.2.2 Effects of hand related lag on discrete manual performance(EHA_D)

The goal of this experiment was to study the effects of hand-related lag in the manual discrete task. The subject performed the task using CyberGlove. The independent variables were (i) hand-related lag, (ii) target distance, and (iii) target width. The modified Fitts' law to model the effect of lag in virtual environment was also discussed. This experiment is reported in chapter 6 of this thesis.

4.2.3 Effects of combined hand and head related lags on discrete manual performance (EHA&HE_D)

This experiment was different from the previous experiments, since both the effects of hand and head-related lags were studied. The main purpose of this study was to study the interaction between the hand and head related lags. The independent variables manipulated in this experiment were (i) hand related lag, (ii) head related lag, (iii) target width, and (iv) target distance. This experiment is reported in chapter 7 of this thesis.

4.2.4 Effects of combined hand and head related lag on continuous manual tracking performance (EHA&HE_C)

This experiment was similar with the previous experiment, except a continuous tracking task was used. The behavioral characteristics of the subjects were also analyzed in the frequency domain. As in the previous experiment the independent variables manipulated in this experiment were (i) hand-related lag, (ii) head-related lag. This experiment is reported in chapter 8 of this thesis.

A logical flow chart of experiments is shown in Figure 4-1 below.

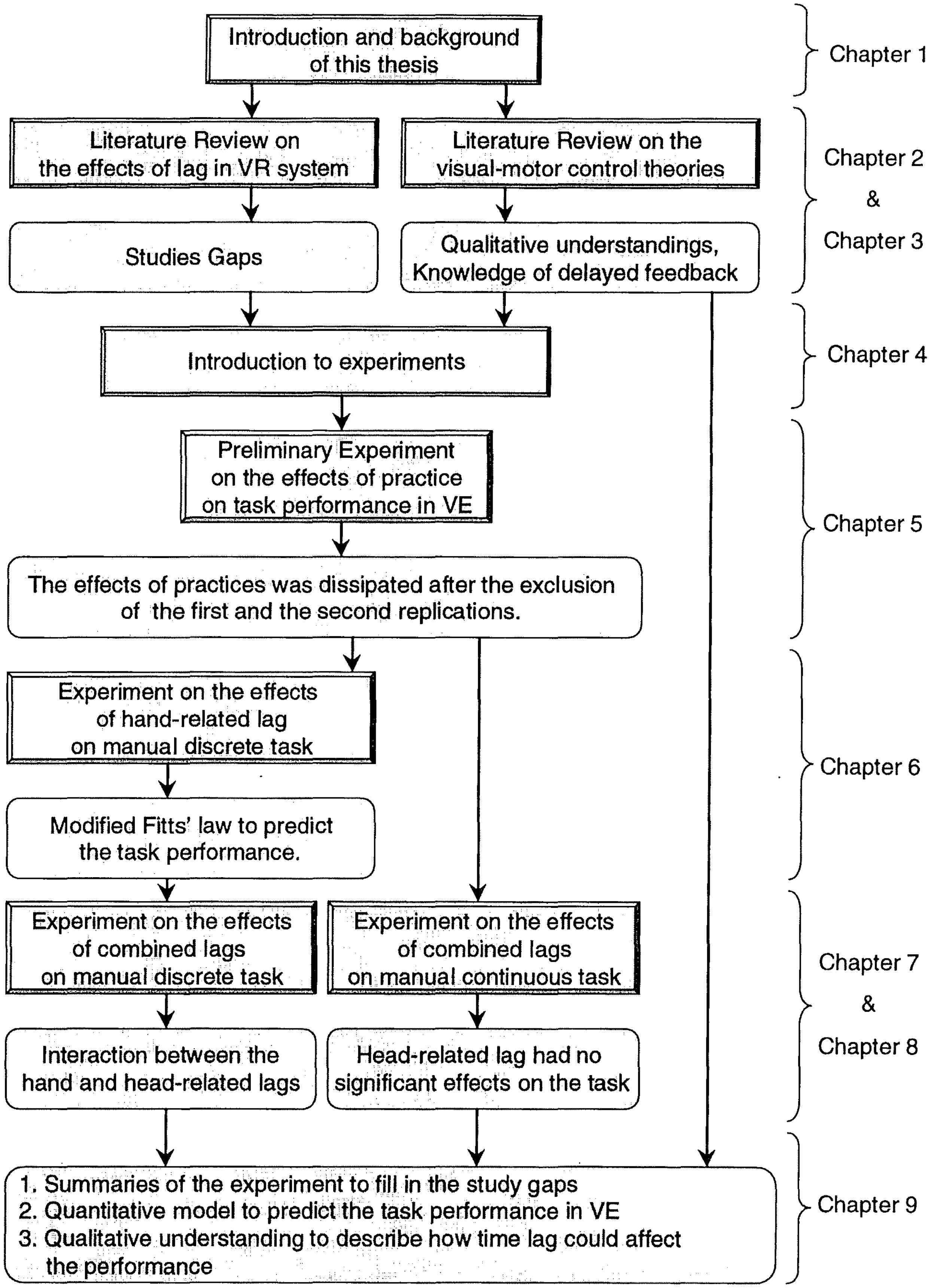

Figure 4-1: Logical flow chart of the experiments

4.3 Measurements

The measurement of the dependent variables were the same in the first three experiments, a discussion of the definition of these measurements is presented in this section.

4.3.1 Measurements in Experiment 1,2,3 (EP_D, EHA_D, EHA&HE_D)

Head reaction time is the interval measured between the onset of the stimulus and the initiation of the head movement response (Boff and Lincoln, 1988). In this study, the time at which a moment of a head response was initiated was referred to as t_i, where t_i was the first moment at which the 'virtual' finger tip left the starting square (i.e., the starting square marker position (left) - see Figure 4-2).

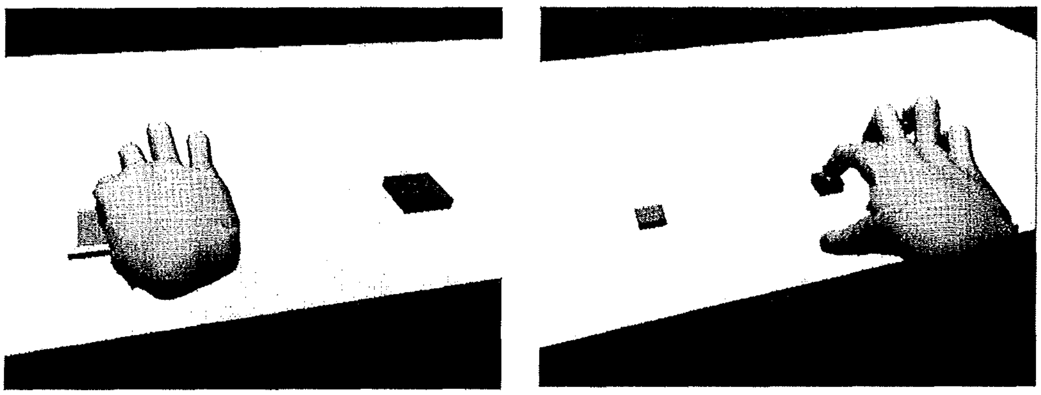

Figure 4-2: Snapshots of the task, subject's finger on the starting square (left), subject's finger pressing the target square (right).

In the presence of an imposed hand-related lag, the hand-related lag was subtracted from t_i so that the measured head reaction time was not contaminated directly by the lag.

<u>Hand movement time</u> is the interval measured between the time at which the hand first moved (t_i) and the time at which the 'virtual' finger tip first made contact with the target (t_c) (Boff and Lincoln, 1988). In the presence of reticle lags, similar to other studies (e.g., Hoffmann, 1992), the duration of the lags would be included in the movement time.

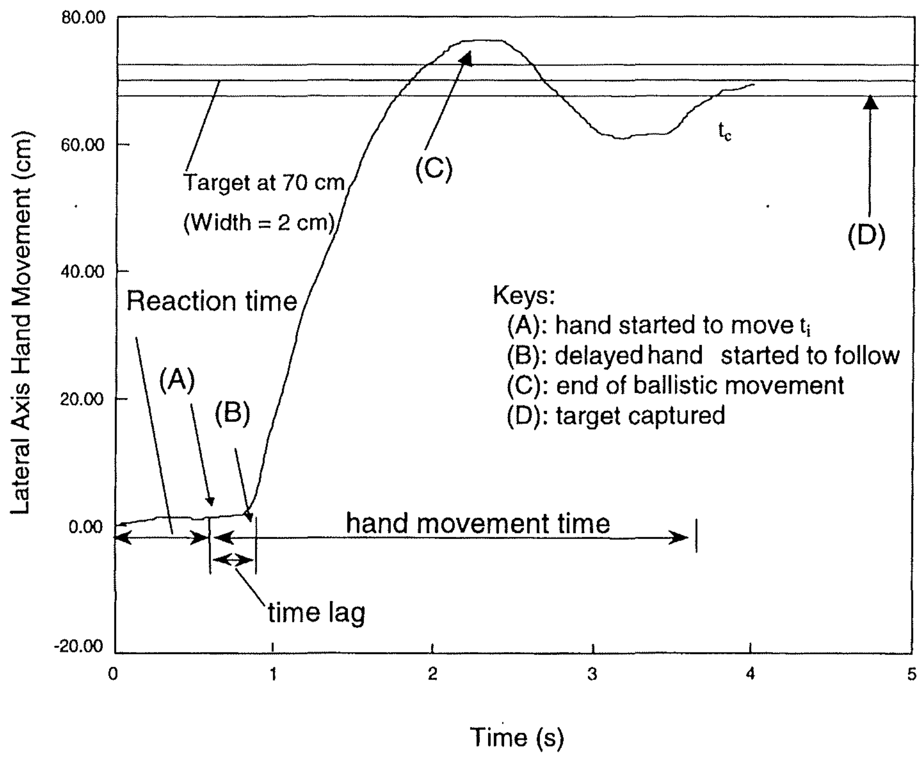

Figure 4-3: A typical time history trace of a 'virtual' finger movement in the presence of lag (data from one subject with target distance = 70cm target width = 2cm, and hand-related lag = 220ms ms).

4.3.2 Measurements used in Experiment 4 (EHA&HE_C)

R.m.s. tracking error is the root-mean-square distance between the center of the target and the center of the tip of the virtual index finger. The calculation formula was shown below:

$$r.m.s.Error = \sqrt{\frac{(ed)^2}{N}}$$

where ed - Error Distance between the center of the target and the 'virtual' finger tip;
N - Total number of the error distance.

Figure 4-4 Calculation formula of the r.m.s. Error Distance between the 'virtual' finger tip and the target.

Cooper-Harper rating is a 10-points scale rating, which was completed based on the bipolar questions. After each run, Cooper-Harper ratings were taken by presenting each subject with these bipolar questions (Figure 4-5), in order to assess the subjective controllability of this Virtual Reality system in different time lag conditions. The Cooper-Harper rating shown in Figure 4-5 is a modified version of CH-rating, the term 'deficiencies' in the original CH-rating was replaced by 'Shortcomings' in this modified version, the changes were made for the better understanding of the Chinese subjects in this experiment.

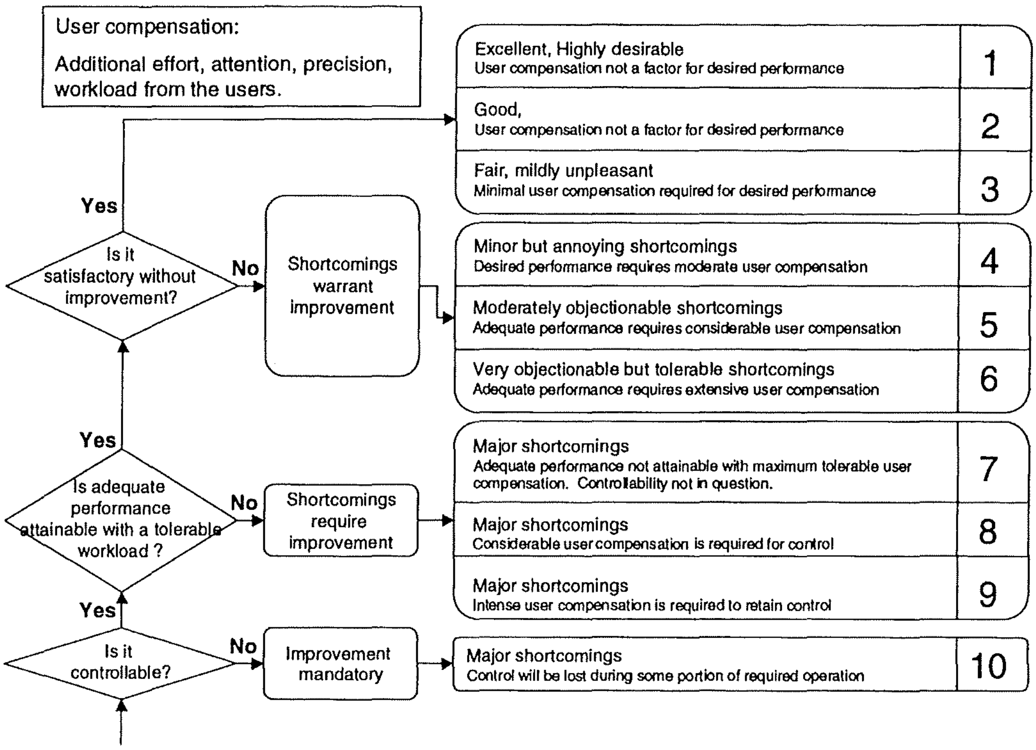

Figure 4-5: Cooper-Harper Rating (measure the controllability of the system)

4.4 Apparatus

An immersive Virtual Reality system was used in these experiments. This system is a composed of a Head mounted display (HMD), 3D tracking system, DataGlove, Real-time rendering 3D software library, and a graphics machine. The following sections describe the specification of the apparatus used in the experiments.

4.4.1 Head Mounted Display (HMD)

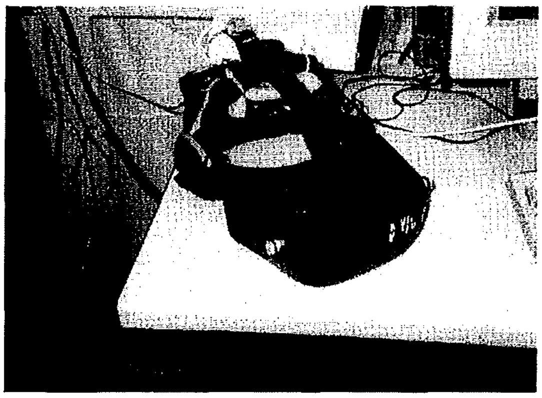

Figure 4-6: VR4 Head Mounted Display (HMD)

Inside the Head Mounted display, there are two Liquid Crystal Displays (LCD), which display the video information that feed from the two input channels respectively. By using this, the users can view or immerse into the 3D Virtual Environment stereoscopically. Viewing the world stereoscopically can improve the sense of depth perception very much, since it is one of a very important for humans to perceive depth information.

The head-mounted display used in this study was VR4 from Virtual Research. It contains two active matrix LCDs, one at each eye correspondingly. The resolution of the LCD is 742*230 color elements per eye. The field-of-view (FOV) of this head mounted display is 48° horizontal * 36° vertical and it's weight is 0.935kg.

4.4.2 Polhemus Fastrak 3D sensor

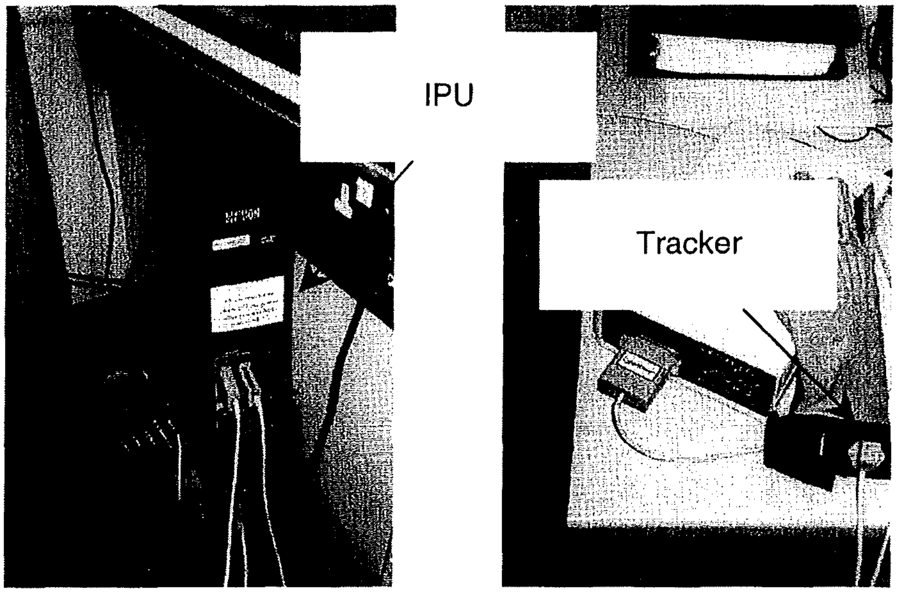

Figure 4-7: Polhemus 3SPACE Fastrak tracking system (IPU is the electronics unit to transform the signals into the position and orientation data; tracker is to detected the 6-dof position inside the magnetic field)

When the user was moving his hand or moving his head, the device to detect his most updated position and orientation is a 3D tracking system, which reported 6 degree-of-freedom coordinates (Position: X-[lateral], Y-[up and down], Z-[fore and aft], Orientation: Pitch, Yaw, Roll).

The 3D tracking system used was Polhemus 3SPACE Fastrak. It is a electromagnetic, six-degree-of-freedom tracking instrument. The static accuracy is 0.08 cm RMS for position, and 0.15° RMS for receiver orientation. The resolution is 0.005 cm/cm of range, and 0.025°. The update rate of the system with two receivers is 60Hz.

4.4.3 CyberGlove

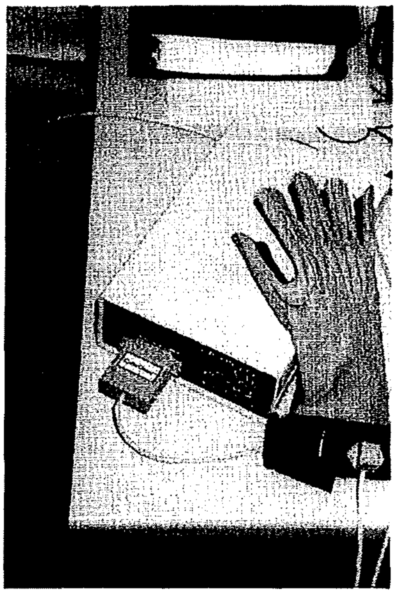

Figure 4-8: Virtual Technologies CyberGlove

To allow the user to interact with the 3D virtual world effectively, a CyberGlove by Virtual Technologies was used. Inside the CyberGlove there are 18 blending sensors, which detect the blending angles of each joint of the fingers and the wrist.

4.4.4 Real-time Rendering 3D library

The real-time 3D graphics engine used in this study was WorldToolKit Release7 from Sense8 Corporation. It is a cross-platform C/C++ software development system for building high-performance, real-time, integrated 3D applications for scientific and commercial use.

WorldToolKit R7 has a function library and end-user productivity tools, needed to create the experiments and the virtual tasks. With the high-level application programmer's interface (API), the experiments can be developed relatively easier and faster. WorldToolKit R7 also supports the interface devices, Polhemus Fastrak tracker, and CyberGlove, which were used in our experiments. It further shortened the development time.

4.4.5 Rendering Machine

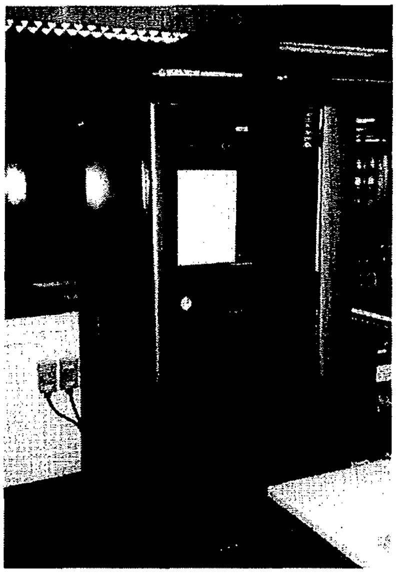

Figure 4-9: Silicon Graphics Onyx 2 Computer

The computer used in this Virtual Reality system was Silicon Graphics Onyx2 machine with two parallel R10000 processors. It is a well known graphics engine used in Virtual Reality labs worldwide. This visual workstation can ensure the minimized system lag in this experimental environment.

4.4.6 Imposed time lag generation

During the beginning of each frame, the 3D library update the most updated information of the trackers. Due to the transmission rate limitation, the update rate of the trackers was limited to 18 times per second, with each frame time at 55 ms. This 55 ms was the system lag of the experimental system, the imposed time lag was the time lag imposed onto this system lag, and it was a multiple of the system lag time(i.e. 110ms, 165ms...). The imposed lag was achieved by queuing up tracker updated record and executing a previously received record. For example, with two frames time delayed, the imposed time lag was 110 ms, and the actual lag 165ms (110ms plus the system lag).

4.5 Modelling and Analysis techniques used in the experimentation

In this thesis, a comprehensive study of the effect of lags in virtual environment was produced. In order to achieve this goal, some modelling and analytical techniques were used. The following sections introduce these techniques together with, reference literature, which applied the same techniques.

The modelling technique used in this thesis were (i) Conceptual modelling, and (ii) Empirical modelling. The frequency domain analysis was used to analyze the behavioral characteristics of the subjects in the fourth experiment (EHA&HE_C).

4.5.1 Modelling

To analyze the system, we must first understand the relationship among the variables. The illustration of how the variables in a system relate to each other is called the 'model' of the system. A model can be a mathematical expression or a graphical representation. In order to closely analyze the effects of lags on task performance in Virtual Environment, two modelling methods were used: conceptual modelling and empirical modelling. In this section, an introduction and example of the modelling is discussed.

4.5.1.1 Conceptual Modelling

Conceptual modelling is one of the simplest methods to illustrate the relationship among variables in a system. Using block diagrams to represent variables, and arrows to represent the relationship and information flow of the variables, the system variables can be shown clearly. This clear representation of the variables can improve the understanding of the system. This graphical representation of the system was widely used for design and illustration purpose.

An example of the conceptual modelling can be found in Ware (1994b). They used a conceptual model to illustrate the information flow of a Virtual Reality system, see Figure 4-10.

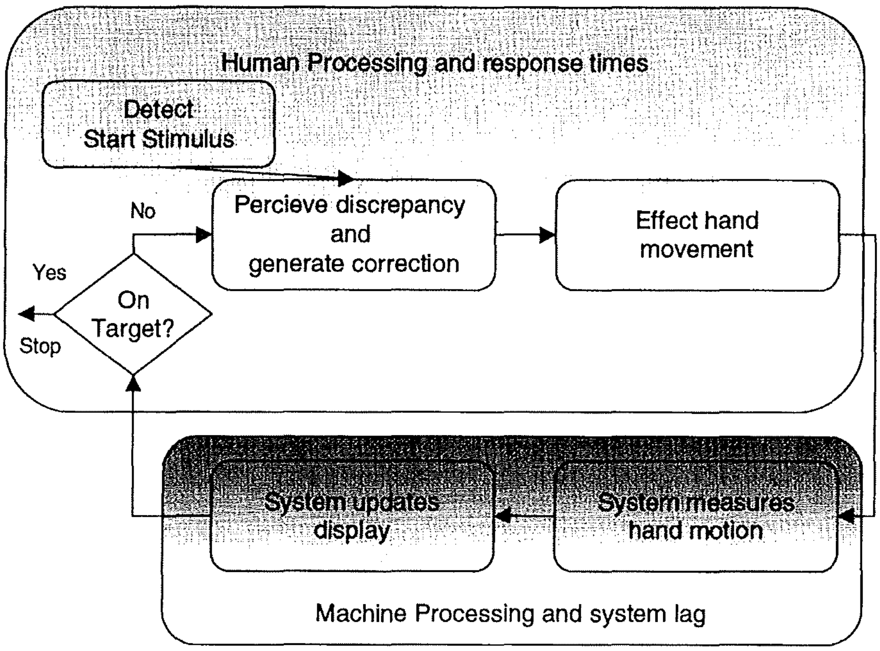

Figure 4-10: Conceptual Model to illustrate the control loop in a VR system

From this model, we can see a clear representation of how and where the time lag was involved in the Virtual Reality system. In this thesis, a conceptual model of how time lags could affect the task performance in VR system was reviewed and presented. This model is discussed in the conclusion chapter.

4.5.1.2 Empirical Modelling

Other than conceptual modelling, empirical modelling was also used. Using conceptual models, the 'what' and 'how' and 'where' information can be formulated, however, the 'how much' information was unknown. Therefore, it was necessary to use a mathematical expression to describe the relationships among the variables. From these models 'how much' the time lags affect the task performance in VR system can be formulated and predicted.

Regression analysis is often used for empirical modelling. From the observed data a linear mathematical model can be formulated. Regression is concerned with the prediction of a dependent variable, y, on the basis of information provided by other independent variables (x_i). In different conditions, the dependent variable, y, can be observed. By fitting y to a linear combination of x_i, a linear regression model can be formulated. There were many variations of how to fit the models, one of the most famous methods was least-squares, however, the basic goal of these methods, was to find out the parameters of the x_i variables, so that it can describe the most variation of the dependent variable (y).

Ware (1994b) used a regression model to represent the effects of lag in Virtual Reality system. Basically they had used a modified Fitts' law to predict the task performance in a Virtual Reality system with lag.

4.5.2 Frequency domain analysis

Sometimes the behavioral analysis of the movement may be complicated in time domain analysis, because the subject's movement consists of different movement patterns. That was why the frequency domain analysis is frequently used in behavioral analysis. Using the frequency domain analysis, the fundamental physical interpretation can be formulated from the transfer function *G(z)*, which is the complex number $G(e^{i\omega})$. Using this complex number, the amplitude and phase shift of the subject's movement can be calculated. The advantage of this method is that the behavior of the subject can be represented clearly in different frequencies.

Many of researchers have used frequency domain analysis. So *et al.* (1995b), for example used frequency domain analysis to analyze the behavior of the subject in a Virtual Reality system with time lag. They found that the behavior of the subjects fluctuated after 0.8Hz of the target movement (input).

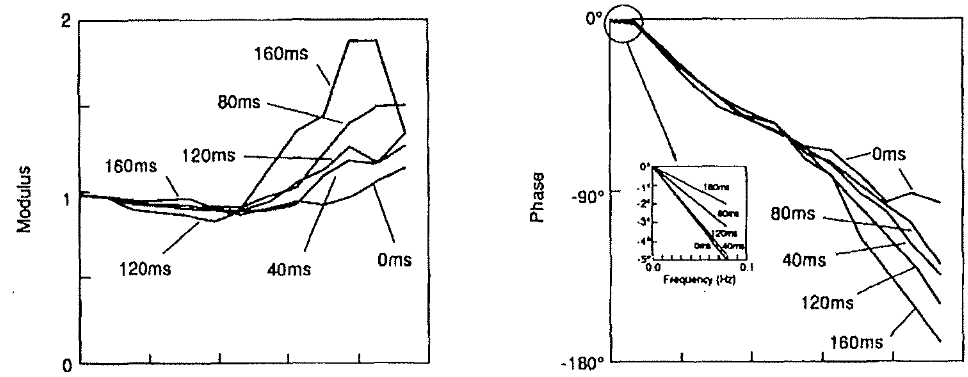

Figure 4-11: An example of Bode Plot representing the behaviour of the subjects in different lag conditions (So *et al.*, 1995b)

CHAPTER 5 Effects of practice on target-directed discrete control performance in a Virtual Reality system with time lags

5.1 Introduction

This chapter describes a preliminary experiment studying the effects of practice on discrete manual control performance in the presence of head and hand-related lags. The objective of this preliminary experiment was to ascertain the effects of practice on discrete manual control performance. This finding served as the preliminary experiment to verify the experimental setup of Experiments 2 and 3 on discrete manual tasks.

5.2 Objectives

The objectives of this experiment were to: (i) study the effects of practice on discrete manual control performance in the presence of head and hand-related lags and (ii) investigate the number of replications needed to dissipate the significant effect of practice.

5.3 Task, procedure, and participants

Subjects were asked to tap the tip of their 'virtual' index fingers between a starting pad and a finishing pad on a horizontal 'virtual' table' as fast as possible (Figure 5-1). As shown in Figure 5-1, the tip of the 'virtual' index finger was coloured in yellow as a visual cue to the subjects. Tactile and force feedback were provided by placing a 'real' table at the same spatial location of the projected 'virtual' table. The VR4 HMD was non-see-through and the subjects could not see the 'real' environment. Twelve male participants took part in the experiment. They were university students and staff and their ages ranged from 19 to 40 years. After receiving instructions and giving written consent, a practice trial without imposed lags was given so that the subjects could become familiarized with the Virtual Reality (VR) system. Subjects were then presented with eight repeated tasks of tapping in the presence of 220 ms imposed head and hand-related lags (imposed on the 55 ms inherent system lag). Six different target distances (distance between the starting and the finishing points, D) and the target width (width of the starting and finishing pads, W) were used through the experiment (D = 10.16, 20.32, 30.48 40.64, 50.8, and 60.96 cm and W = 6.35 cm).

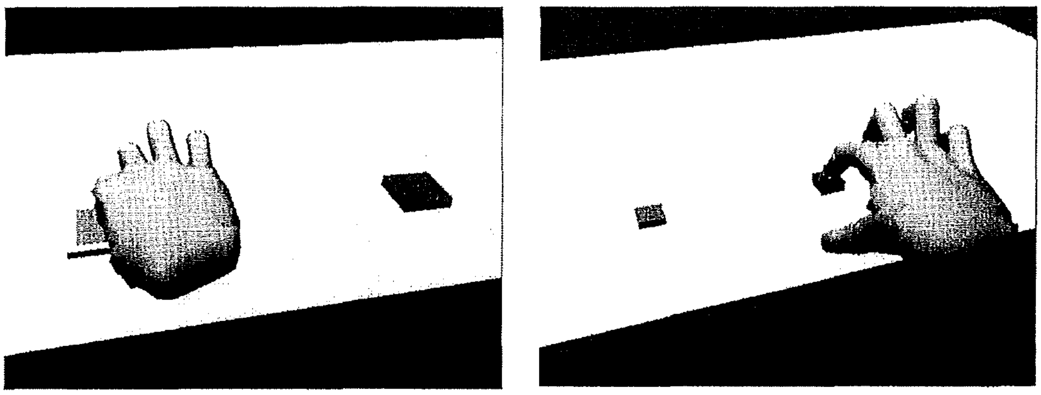

Figure 5-1: Snapshots of the task, subject's finger on the starting square (left), subject's finger pressing the target square (right).

At the beginning of each tapping task, subjects were required to place their 'virtual' index fingers on top of the starting pad. When the starting pad changed colour, they would then move their fingers towards the target pad as fast as possible upon collision with the tip of 'virtual' index fingers the finishing pad changed colour. Once the target pad changed colour, subjects were required to move their fingers back to the starting pad and tap it. The tapping trial was repeated six times and the task was finished. Subjects then repeated the same tasks with a different target distance. As the repetition increased, however, the subject's arm and finger muscles might become familiar with the movement and, hence, the task would gradually become an open-loop operation without the use of any visual feedback. In order to minimize the effect, the order of the target distances was randomized. Altogether, there were eight repetitions, within each repetitions there were 6 different target distances. This tapping task has been the typical task in many studies verifying the Fitts' law in a real environment (e.g., Fitts and Posner, 1967; Hoffmann, 1992). The positions of the 'virtual' index finger tip was measured and the target-directed hand-movement time (MT) was defined as the time period between the moment when the 'real' index finger started to move and the moment when the tip of the 'virtual' finger contacted with the finishing pad.

5.4 Results

The mean hand-movement times of the six discrete movements of the twelve subjects is shown in Figure 5-2 as functions of the number of repetitions. It can be seen that as the number of repetitions increased, the movement time decreased. However, the decrease leveled off after the second replication.

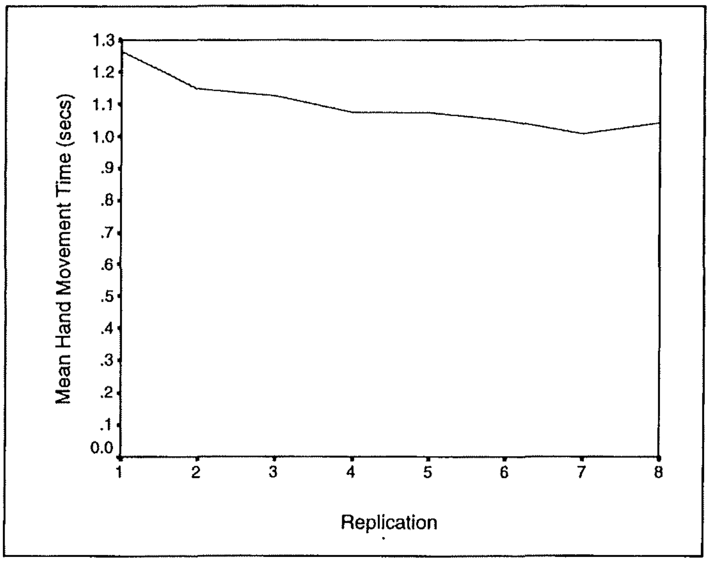

Figure 5-2: Plot of the effects of practices, MT vs Replication (Practices)

An ANOVA (Table 5-1) was conducted to study the effects of practice and the trials on the hand movement time. All main effects were significant in this ANOVA, Trial ($F_{5,3332}$=13.77, $p < 0.0001$), Replication ($F_{7,3332}$=9.16, $p < 0.0001$), ID ($F_{5,3332}$=172.85, $p < 0.0001$), and Subject ($F_{11,3332}$=27.12, $p < 0.0001$).

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Trial	5	23.035324	4.607065	13.77	0.0001
Replication	7	21.455991	3.065142	9.16	0.0001
ID	5	289.097268	57.819454	172.85	0.0001
Subject	11	99.789709	9.071792	27.12	0.0001
Trial * ID	25	13.697066	0.547883	1.64	0.0239
Replication * ID	35	18.457840	0.527367	1.58	0.0170
Trial * Replication	35	8.049058	0.229973	0.69	0.9175
Error	3332	1114.559514	0.334502		

Table 5-1: ANOVA table on hand movement time (included all replications)

SNK Grouping	Mean	N	TRIAL
A	1.27632	576	1
B	1.09570	576	3
B	1.08574	576	2
B	1.07737	576	4
B	1.04022	576	6
B	1.03213	576	5

Table 5-2: SNK Grouping table of Trial on hand movement time (included all replications)

SNK Grouping	Mean	N	Replication
A	1.28050	432	1
B	1.15613	432	2
C B	1.12382	432	3
C B	1.06515	432	8
C B	1.06234	432	4
C B	1.05055	432	5
C	1.04037	432	6
C	1.03110	432	7

Table 5-3: SNK Grouping table of Replications on hand movement time (included al replications)

The SNK group of TRIAL on hand movement time suggested the exclusion of the first trial in the analysis (Table 5-2). After the first trial was excluded from the analysis, the trial became insignificant ($F_{4,2769}$=1.57, p> 0.1798). Although the SNK results of replication (Table 5-3) suggested the exclusion of the first replication in the analysis, the effects of replication was still significant ($F_{6,2419}$=2.47, p<0.022) after the exclusion. This significant effect suggested the further exclusion of replications. Finally, after the first trial and the first and the second replications were excluded from the analysis, both trial and replication became insignificant.

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Trial	4	1.276752	0.319188	1.16	0.3262
Replication	5	2.104648	0.420930	1.53	0.1769
ID	5	137.768276	27.553655	100.21	0.0001
Subject	11	60.866988	5.533363	20.12	0.0001
Trial * ID	20	4.304468	0.215223	0.78	0.7372
Replication * ID	25	8.346408	0.333856	1.21	0.2132
Trial * Replication	20	3.285775	0.164289	0.60	0.9172
Error	2069	568.876130	0.274952		

Table 5-4: ANOVA table on hand movement time
(excluded the first trial, the first two replications)

5.5 Discussion

The experiment results showed that the effects of repetitions had significant effects on the hand movement time. After the exclusion of the first and second replications, the effects disappeared. This suggested that the number of replications needed for experiments on the manual discrete task, should be at least 3 or more. Therefore, the effects of repetitions can be prevented.

From this experiment it was observed that after the first trial, the movement of the subjects were shifted to feed-forward manner without visual feedback. The subjects memorized the target distance after the first trial was performed, which is not expected in the experiment of this study. Therefore, the later two experiments on discrete task only one trail will be used instead of 6.

CHAPTER 6 Effects of hand-related lag on discrete manual performance (EHA_D)

6.1 Introduction

In this chapter, an experiment studying the effects of hand-related lag in a manual discrete task is presented. Factors investigated in this experiment included repeated runs, duration of hand-related lag, target width, and target distance. This experiment is concerned with the effects of hand-related lag on a Fitts' type discrete tracking task. The purpose of this study was to determine the effects of and the interactions among hand-related lag, target distance, and target width. A model of the effects of hand-related lag based on Fitts' law will also be developed.

6.2 Objectives, hypotheses, and variables

The objectives of this study were to (i) investigate the effect of hand-related lag on manual discrete tracking task in a virtual environment, and (ii) model the performance of discrete manual task in the presence of lags. The hypotheses were:

(i) hand movement time will increase with increasing hand-related lag,

(ii) with a constant lag, the relationship among movement time, target width, and target distance will obey Fitts' law,

(iii) the effects of lag will have no significant interaction with the effects of target distance, and

(iv) the effects of lag will have a significant interaction with the effects of target width.

The latter two hypotheses were based on the findings of a recent study concerning the effects of head movement related lag in experiment 1 (HeD). The dependent variables were r.m.s. head movement, hand movement time, and hand reaction time. In this experiment, target width (1cm, 2cm, 3cm, 4cm), target distance (14cm, 24cm, 41cm, 70cm), and imposed hand-related lag (0ms, 55ms, 110ms, 220ms, 440ms) were manipulated. The base lag of the experiment environment was 55 ms.

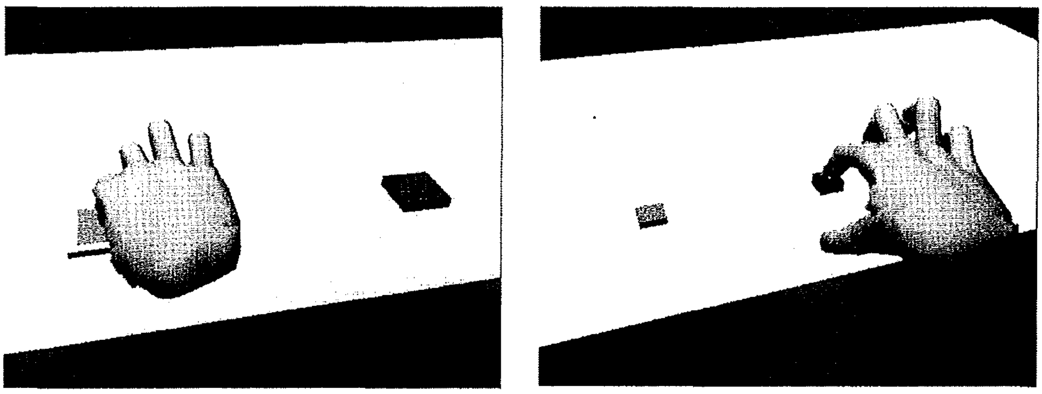

Figure 6-1: Snapshots of the task, subject's finger on the starting square (left), subject's finger pressing the target square (right)

6.3 Task, procedure, and participants

Subjects were asked to hit a target square as fast as possible using the index finger of the virtual hand. When the square was hit, the color of the square changed while the finger needed to remain on the target for three frames (i.e., about 165 ms) until the target square disappeared. The virtual world was carefully calibrated spatially to match the real world, so that when the subjects were pressing on a table in Virtual Environment, they were also pressing on a table in the real world. This ensured that the subjects had tactile feedback.

At the beginning of the experiment, a detailed explanation of the task was given to the subjects. After that, there was a series of practice tasks without lag to familiarize subjects with the virtual world, the apparatus and the task requirement. These practice tasks can provide the subjects enough time to learn and adopt a hand gesture, so that the finger was not visually obstructed by the virtual hand. This was followed by 5 hand-related lag conditions. Each condition had 16 runs exhausting the 16 combinations of four target four distances and target widths. The order of presenting the runs and conditions were randomized. Each condition was repeated 3 times. There was a one-minute rest between each condition.

Twelve healthy males aged between 19 to 24 participated in this experiment. They were paid HK$60 as a compensation for their time.

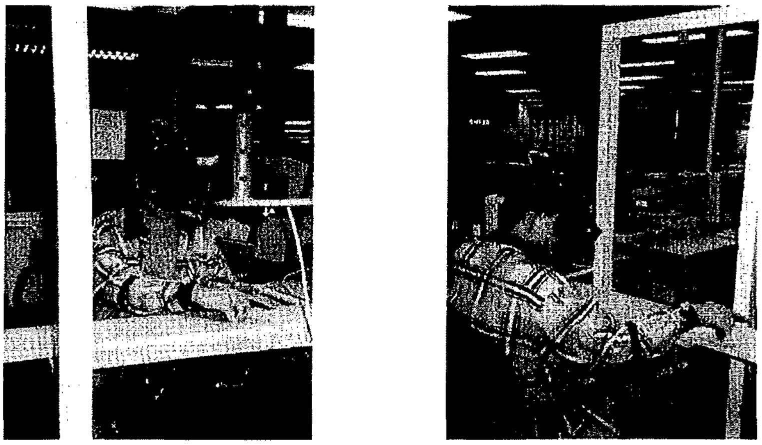

Figure 6-2: Apparatus setup the hand position at the starting point (left), the subject's finger position at the target square (right).

6.4 Results

An ANOVA was conducted on hand movement time data collected (Table 6-1). A significant effect of replications was found ($F_{2,2568}$=9.16, p<0.0001). The mean hand movement times with the three replications are illustrated in Figure 6-3. As shown in the figure, mean performance improved during the first replications and this improvement flattened out during the second and third replications.

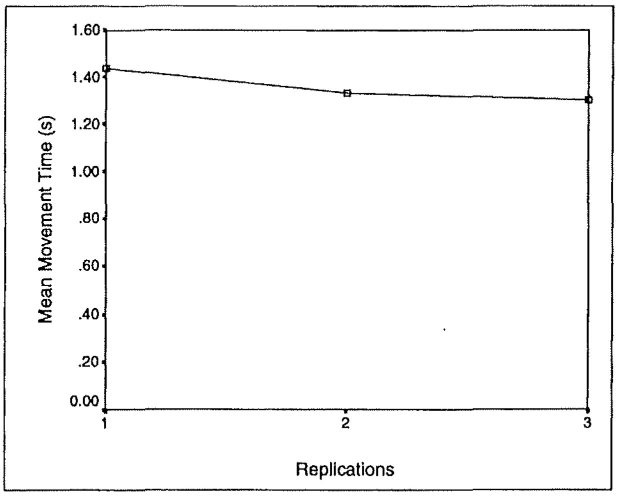

Figure 6-3: Plot of the effects of practices, MT vs Replication (Practices).

Source	**Df**	**Sum of Square**	**Mean Square**	**F-Value**	**Pr > F**
Hand Lag	4	390.851671	97.712918	177.49	0.0001
Subject	11	356.446389	32.404217	58.86	0.0001
Replication	2	10.082068	5.041034	9.16	0.0001
ID	15	513.776870	34.251791	62.22	0.0001
Hand Lag * ID	60	64.775275	1.079588	1.96	0.0001
Subject * Hand Lag	44	76.755986	1.744454	3.17	0.0001
Hand Lag * Replication	8	5.179136	0.647392	1.18	0.3096
Subject * ID	165	229.344846	1.389969	2.52	0.0001
Error	2568	1413.76183	0.55053		

Table 6-1: ANOVA table on hand movement time (included all replications)

Source	Df	Sum of Square	Mean Square	F-Value	Pr > F
Hand Lag	4	266.325312	66.581328	149.98	0.0001
Subject	11	182.738616	16.612601	37.42	0.0001
Replication	1	0.375593	0.375593	0.85	0.3578
ID	15	329.196547	21.946436	49.43	0.0001
Hand Lag * ID	60	76.677624	1.277960	2.88	0.0001
Subject * Hand Lag	44	52.156899	1.185384	2.67	0.0001
Hand Lag * Replication	4	4.429989	1.107497	2.49	0.0412
Subject * ID	165	131.691304	0.798129	1.80	0.0001
Error	1613	716.08775	0.44395		

Table 6-2: ANOVA table on hand movement time (excluded the first replication)

Table 6-2 shown the ANOVA table on hand movement time (all ANOVA tables in this thesis are full completed ANOVA with 3 or higher-ways interactions included in the error term). After the first replication was excluded from the ANOVA analysis, the effect of replication was no longer significant ($F_{1,1613}$=0.85, p<0.3578). As a result, the data from the first replication was excluded in all of the subsequent analyses. Following the traditional way to analyze the results as reported in Hoffmann (1992) and Mackenzie and Ware (1993), an ANOVA was conducted to investigate the effects of hand-related lag and Index-of-Difficulty (ID). Both the lag and the ID had a significant effect on hand Movement Time (MT) (Hand lag: $F_{4,1613}$=149.98, p<0.0001; ID: $F_{15,1613}$=49.43, p<0.0001). The significant interactions between the effects of hand-related lag and the effects of ID was found ($F_{60,1613}$=2.88, p<0.0001). This suggests that the effects of lag is a multiple of ID, and this also agrees with the findings of Hoffmann (1992) and Mackenzie and Ware (1993), in which they proposed the multiplicative relation between the effects of lag and Index-of-Difficulty (ID).

Source	Df	Sum of Square	Mean Square	F-Value	Pr > F
Hand Lag	4	266.325312	66.581328	148.63	0.0001
Subject	11	182.738616	16.612601	37.08	0.0001
Replication	1	0.375593	0.375593	0.84	0.3600
Width	3	165.573920	55.191307	123.20	0.0001
Distance	3	153.201596	51.067199	114.00	0.0001
Hand Lag * Width	12	46.191671	3.849306	8.59	0.0001
Hand Lag * Distance	12	8.568316	0.714026	1.59	0.0867
Subject * Hand Lag	44	52.156899	1.185384	2.65	0.0001
Hand Lag * Replication	4	4.429989	1.107497	2.47	0.0427
Subject * Width	33	30.002909	0.909179	2.03	0.0005
Subject * Distance	33	56.652229	1.716734	3.83	0.0001
Distance * Width	9	10.421031	1.157892	2.58	0.0059
Error	1748	783.041557	0.447964		

Table 6-3: ANOVA table on hand movement time (separated ID into width and distance)

A second ANOVA was performed investigating the effects of lag, target distance, and target width (Table 6-3). In other words, the ID was separated into its components during the analysis. Not surprisingly, significant main effects were identified for hand-related lag ($F_{4,1748}$=148.63, p<0.0001), target width ($F_{3,1748}$=123.2, p<0.0001), and target distance ($F_{3,1748}$=114.0, p<0.0001). Although no significant interaction was found between the effects of lag and the effects of target distance ($F_{12,1748}$=1.59, p>0.0867), a significant interaction between target width and hand lag was identified ($F_{12,1748}$=8.59, p<0.0001). This suggests that while the effects of lag is not a multiple of target distance, it is a multiple of target width or (target width)$^{-1}$ as explained in the Discussion Section.

SNK Grouping	Mean	Hand Lag
A	1.94651	440
B	1.46469	220
C	1.24834	110
D	1.05010	55
E	0.86974	0

Table 6-4: SNK grouping of Hand-related lag on hand movement time

SNK grouping (Table 6-4) showed all five hand-related lags conditions were significantly different from each other. This suggested that the Hand movement times increased significantly with hand-related lags of 55 ms or more.

6.5 Discussion

6.5.1 Model development to describe the effects of hand-related lag on target-directed discrete hand Movement Time (MT)

In Hoffmann's study, the dependency between the effects of lags and the effects of the ID was based on the assumption that the subjects used a 'move-and-wait' strategy throughout the entire duration of the target-directed hand movement (Hoffmann, 1992). In simple terms, Hoffmann's model suggests that a user will split the hand movement into n steps and each step will consist of a discrete movement and a waiting period equivalent to the lag duration. The logic behind this strategy is that the subject would need to see the delayed effects of each step before proceeding to the next step of hand movement. With this 'move-and-wait' strategy, the effect of the lag is proportional to the number of steps (n), which, in turn, is a function of both the target distance (D) and the target width (W). Hence, there is an interaction between the effects of lags and ID. In the preliminary experiment 1, no evidence of this type of movement was found. Instead, target-directed hand movements in the presence of lags were found to consist of two distinct stages: (i) a smooth continuous ballistic hand movement from the starting point towards the target, followed by (ii) a series of 'move-and-wait' movements. A typical 'virtual' finger tip movement in the presence of lag is shown in Figure 6-4. Figure 6-5 illustrates the various stages of a modelled finger tip movement. As shown in Figure 6-5, the movement time (MT) between the moment the finger moves and the moment the 'virtual' finger tip is resting on the target is the sum of three components:

i. time lag, L, (point A to B);
ii. movement time of the first ballistic movement from the starting point to the first stopping point near the target (point B to C); and
iii. movement time of a series of 'move-and-wait' movements homing into the target (point C to D).

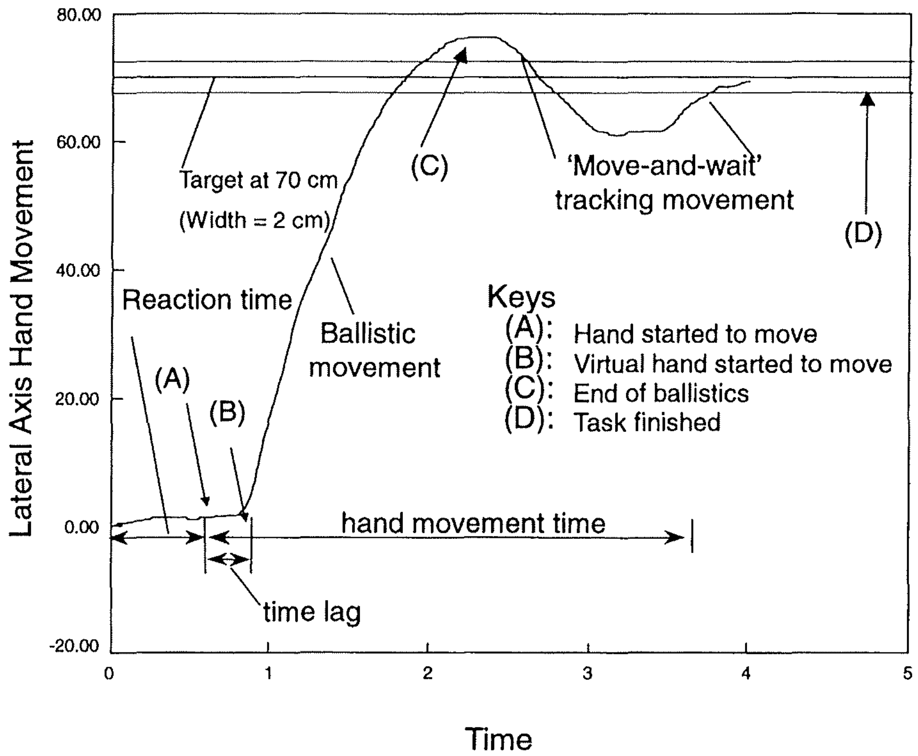

Figure 6-4 A typical time history trace of a 'virtual' finger movement in the presence of lag (data from one subject with target distance = 70cm target width = 2cm, and hand-related lag = 220ms ms).

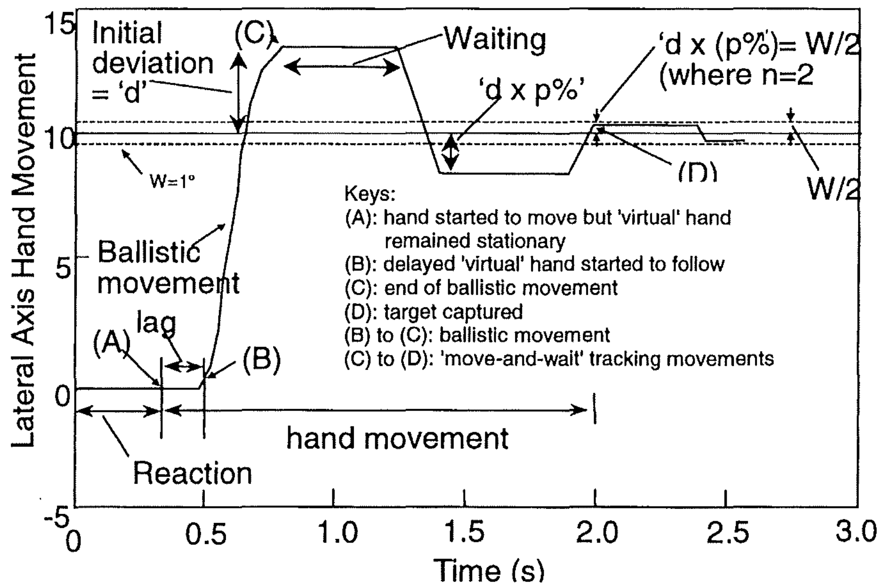

Figure 6-5 A proposed model of target-directed finger movements in the presence of lag with ballistic and 'move-and-wait' movements.

During the first ballistics movement towards the target, the operator could not have noticed the effects of lag until they had started to move, by which time the ballistic movement had already been initiated. Therefore, the first ballistics movement time should be independent of lag. If there were no lag, this ballistic movement would be enough to move the 'virtual' finger tip from the starting point to the target. However, because of the lags, the 'virtual' finger tip would miss the target and subjects would be forced to make a series of 'move-and-wait' adjustments to compensate for the extra deviation (see Figure 6-4) due to the lags. In other words, the time taken by the first ballistic movement would be approximately equal to the movement time in the absence of lag ($MT_{lag=0}$). As explained in Hoffmann (1992), each of the 'move-and-wait' movements has a duration equal to the sum of the time lag (L), the reaction time (RT), the decision time (DT), and the movement time (t_m). It is assumed that t_m can be absorbed into the lag (L) and that RT and DT are constants represented by t_{rd}. The time taken by n 'move-and-wait' movements would, therefore, be [n x (L + t_{rd})] and the movement time (MT) of the whole target-directed head movement would be:

$$MT = \underset{\text{(lag)}}{L} + \underset{\text{(ballistic movement)}}{MT_{lag=0}} + \underset{\text{(move-and-wait movements)}}{[n \times (L + t_{rd})]}. \qquad (1)$$

In order to move the 'virtual' finger tip towards the target, the amplitudes of each successive 'move-and-wait' movement will need to be reduced. It is assumed that the rate of reduction in amplitude is p% where p is less than 100. When the 'virtual' finger tip can finally rest on the target, the number (n) of 'move-and-wait' movements would satisfy the following condition:

Initial deviation (d) x $(p\%)^n$ = target width (W) / 2

$$d \times (p\%)^n = W/2$$

$$(p\%)^n = W/2d$$

Taking logarithm to the base of 2:

$$n \times \log_2(p\%) = \log_2 W/2d$$

$$n = [(\log_2 W/2) - (\log_2 d)] / \log_2(p\%)$$

2/W is used instead since it is closer to the target width component in the ID:

$$n = (\log_2 2/W) + (\log_2 l) / \log_2(1/p\%),$$

It is assumed that the initial deviation (d) will be proportional to the lag (i.e., d = X lag, where X is a constant) and 1 / $\log_2(1/p\%)$ can be represented by a constant, Y:

$$n = [(\log_2 2/W) + (\log_2 X \text{ lag})] \; Y$$

$$n = Y \log_2 (2/W) + Y \log_2 (X L) \qquad (2)$$

where X, Y are constants, L is the lag, and W is the target width

Substituting equation (2) into equation (1):

$$MT = L + MT_{lag=0} + [n \times (L + t_{rd})]$$

$$MT = L + MT_{lag=0} + \{[Y \log_2 (2/W) + Y \log_2 (XL)] \times (L + t_{rd})]\}$$

$$MT = L + MT_{lag=0} + Y (L)(\log_2 2/W) + Y (L)\log_2 (XL)$$
$$+ Yt_{rd} \log_2 (2/W) + Yt_{rd} \log_2 (XL).$$

Replacing Yt_{rd} with a constant Z:

$$MT = L + MT_{lag=0} + Y (L)(\log_2 2/W) + Y (L)\log_2 (X) + Y (L)\log_2 (L)$$
$$+ Z \log_2 (2/W) + Z \log_2 (L) + Z \log_2 (X).$$

Substituting the $MT_{lag=0}$ with Fitts' law equation (i.e., $MT_{lag=0} = A + B$ (ID)):

$$MT = L + A + B (\log_2 (2D/W) + Y (L)(\log_2 2/W) + Y (L)\log_2 (X)$$
$$+ Y (L)\log_2 (L) + Z \log_2 (2/W) + Z \log_2 (L) + Z \log_2 (X).$$

Grouping and simplifying the following terms by absorbing the following constants using A,B,C, D ... etc:

Constant term: $A + Z\log_2(X) = A$

Terms with $\log_2(D)$: $B\log_2(D)$

Terms with $\log_2(2/W)$: $(B + Z)\log_2(2/W) = C\log_2(2/W)$

Terms with (L) and $(L)\log_2(L)$: $[1+Y\log_2(X)](L)+Z\log_2(L)+Y(L)\log_2(L) = D(L)$

Terms with $(L)(\log_2 2/W)$: $Y(L)(\log_2 2/W) = E(L)(\log_2 2/W)$

leads to:

$$MT = A + B\log_2(D) + C\log_2(2/W) + D(L) + E(L)\log_2(2/W)$$

Combining the terms '$\log_2(D)$' and '$\log_2(2/W)$' to '$\log_2(2D/W)$' and re-assigning the constants:

$$MT = A + B\log_2(2D/W) + C(L) + D(L)\log_2(2/W)$$

$$MT = A + B(ID) + C(L) + D(L)\log_2(2/W) \qquad (3)$$

Inspection of Equation 3 indicates that while the effects of lag (L) and target width (W) on the movement time (MT) has an interaction, the effects of lag are independent of the effects of target distance (D).

6.5.2 Validating the model with experimental results

With a constant lag, hand Movement Time (MT) increased linearly with the Index-of-Difficulty (ID) and the results of linear regression analyses indicated a R^2 greater than 0.78 (Figure 6-4). Since there are 55 ms system lag in experiment system, the 55ms system lags were included in the regression analysis in addition to the imposed time lags manipulated in the experiments.

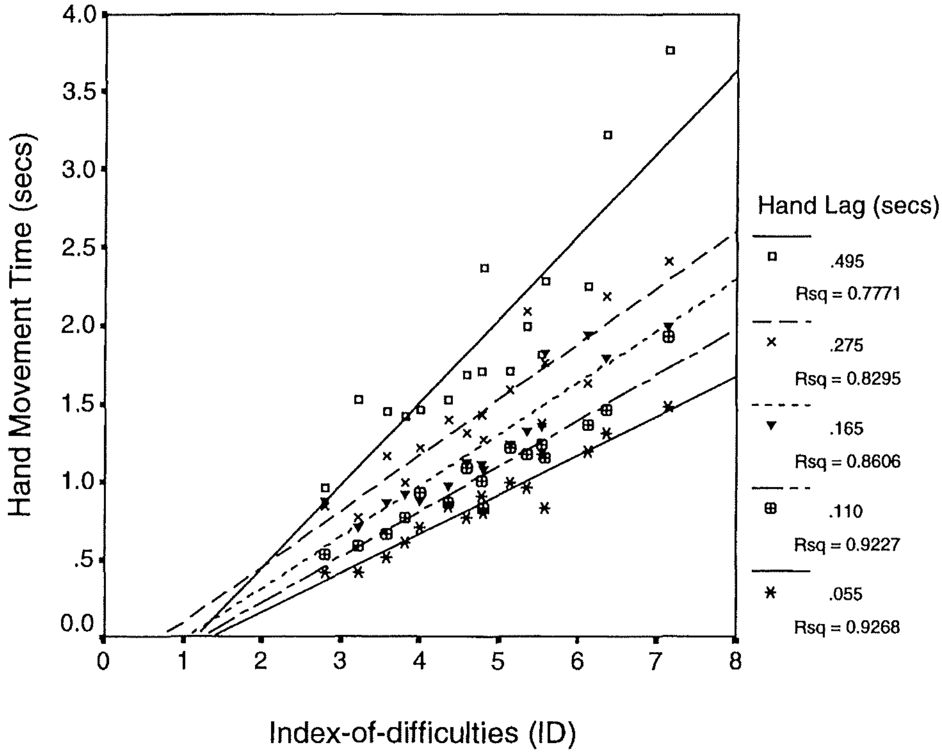

Figure 6-4: Regression plots of movement time and ID, with fixed hand-related lags.

When hand-related lags of 110 ms or greater were imposed, the Movement Times increased significantly ($F_{4,1748}$=148.63, p<0.0001). In 1993, MacKenzie and his colleagues modelled the hand Movement Time in the presence of hand-related lag with a modified Fitts' law (MacKenzie and Ware, 1993). They found that the effect of lag has a significant interaction with ID and proposed to model the effects of lag as a multiple of lag (L) and ID. Their equation was:

$$MT = A + B*ID + C*Lag*ID \qquad \text{Equation 1}$$

Similar with their studies, ID had a significant interaction with hand-related lag ($F_{60,1613}$=2.88, p<0.0001). Further analyses showed that significant interactions only exist between the effects of hand-related lag and target width ($F_{12,1748}$=8.59, p<0.0001), but not between the effects of hand-related lag and target distance ($F_{12,1748}$=1.59, p>0.0867). This finding suggests that the effects of lag only have a multiplicative effect with target width. The model proposed by MacKenzie and Ware (1993) is, therefore, not applicable to this experiment. A possible explanation for the differences between MacKenzie's findings and the results of this study can be found after reviewing a study by Hoffmann in 1992. MacKenzie's model is very similar to that proposed by Hoffmann in 1992 which is based on the assumption of a 'move-and-wait' strategy by the subjects. In other words, when subjects move a hand-controlled pointer from a starting point to a finishing point, they will divide the movement into a series of 'move-and-wait' steps so that the delayed action of each step is seen before they proceed to the next step. In this experiment, such a 'move-and-wait' phenomenon could not be observed. Instead, subjects' hand movements could be divided into two main parts: (i) a ballistic movement which puts the hand on top of (in conditions where there is no lag), or close to (in conditions with lags) the target; and (ii) a series of compensatory tracking movements which move the hand towards the target. This phenomenon has also been reported in the previous experiment on the discrete target-directed head movement in a virtual environment with head movement related lags. The increases in hand Movement Time by lag are mainly due to the increases in the duration of compensatory tracking movements which, obviously, depend on the size of the target. As a result, the effects of lag has significant interactions with target width. Since the compensatory tracking movements will only start after the hand is brought to the vicinity of the target by a ballistic movement, the duration of the compensatory tracking movements are independent of target distance. Hence, the increases in Movement Time due to lags are independent of target distance.

In order to formulate a suitable model to describe the effects of hand-related lag on hand Movement Time (MT), a linear regression analysis was performed. The basic components in this regression model was similar to those in Equation 1 except that Index-of-Difficulty (ID) has been divided into its sub-component: $Log_2(D)$ and $Log_2(2/W)$. Also, hand-related lag (L) is added as a separated term.

The resulting model is:

$$MT = -0.619 + 0.288\,Log_2(D) + 0.127\,Log_2(2/W) + 1.68\,(L) + 1.183\,(L*Log_2(2/W)) + 0.177\,[L*log_2(D)]$$

R^2=0.918

where D - target distance

W - target width

L - hand-related lag

Variable	Df	Parameter Estimate	Standard Error	T for H0: Parameter = 0	Prob > ITI
Interception	1	-0.619166	0.17838245	-3.471	0.0005
$Log_2(2/W)$	1	0.127475	0.04068411	3.133	0.0018
$Log_2(D)$	1	0.287616	0.03533525	8.140	0.0001
Hand Lag	1	1.676463	0.66173348	2.533	0.0114
Lag * $Log_2(2/W)$	1	1.183024	0.15099054	7.835	0.0001
Lag * $Log_2(D)$	1	0.176810	0.13109633	1.349	0.1776

Table 6-5: ANOR Table of the terms in Equation 1

However, an ANOVA analysis of the regression model indicates that all the terms have significant effects ($p<0.001$) on Movement Time (MT) except the term "L*$Log_2(D)$" ($p > 0.177$). This suggests that this term should be excluded from this regression model. After the exclusion, the resulting regression model becomes:

$$MT = -0.813 + 0.327[\log_2(D)] + 0.127[\log_2(2/W)] + 2.555(lag) + 1.183[lag*\log_2(2/W)].$$

$R^2=0.916$

where lag - hand movement lag

W - target width

D - target distance

Variable	Df	Parameter Estimate	Standard Error	T for H0: Parameter = 0	Prob > ITI
Interception	1	-0.812567	0.10612374	-7.657	0.0001
$Log_2(2/W)$	1	0.127469	0.04069282	3.132	0.0018
$Log_2(D)$	1	0.326526	0.02040644	16.001	0.0001
Hand Lag	1	2.555227	0.11560178	22.104	0.0001
Lag * $Log_2(2/W)$	1	1.183038	0.15102286	7.834	0.0001

Table 6-6: ANOR Table of the terms in Equation 1
(Excluded Lag * $Log_2(D)$ term)

Without hand-related lags, hand movements were consistent with the predictions of Fitts' law (i.e., hand movement times were directly related to the 'index-of-difficulty', which is the logarithm of the ratio of target distance to target diameter). Hand movement times increased significantly with hand-related lags of 55 ms or more. The increases in movement times caused by lags increased with decreasing target size but were independent of changes in target distance. It was concluded that an increase in target distance will only increase the index-of-difficulty whereas an decrease in target size will increase both the index-of-difficulty and the effect of lags. A modification of Fitts' law to include the effects of lags on hand movement time is proposed.

To continue the analysis, a new variable CMT_{lag} was introduced, which was the change of the movement time as a function of lags. CMT_{lag} can be calculated as the hand movement time with imposed lags, minus the hand movement times without imposed lags. This variable was used to form a regression model to predict the change of the movement time based on the time lags in the system. From the previous analysis, it was found that effects of lag only had significant interactions with effects of width, so that only hand lag, and hand lag * width were chosen to be included in this regression model. The constant was excluded in this analysis, since the change of movement time was equal to 0 when time lag was equal to 0.

The resulting model was shown below:

$$CMT = 2.304(lag) + 0.969[lag*\log_2(2/W)] \qquad \text{Equation 2}$$

R^2=0.96

where lag - hand movement lag

W - target width

Variable	Df	Parameter Estimate	Standard Error	T for H0: Parameter = 0	Prob > ITI
Hand Lag	1	2.304	0.086	26.907	0.0001
Lag * $Log_2(2/W)$	1	0.969	0.112	8.662	0.0001

Table 6-7: ANOR Table of the terms in Equation 2

A regression model with high R-square was found in this analysis, the purpose of which was to predict the mean rather than individual results, since the interaction between the effects of lag and effects of subjects were ignored.

The third experiment (EHA&HE_D) was to extend the findings to different types of lag (i.e. hand-related lag and head-related lag). The aims were to study the effect of hand and head-related lag and the interaction between them, and also to validate the equation 2 proposed in this chapter.

CHAPTER 7 Effects of combined head and hand-related lags on manual discrete performance (EHA&HE_D)

7.1 Introduction

In this chapter, an experiment studying the effects of combined lags in a manual discrete task is presented. Factors investigated in this experiment included repeated runs, duration of hand-related lag, head-related lag, target width, and target distance. The effects of combined lags on a Fitts' type discrete tracking task was investigated. The purpose of the study was to determine the effects of and the interactions among hand-related lag, head-related lag, target distance, and target width. A model of the effects of hand and head–related lag based on Fitts' law will also be developed.

7.2 Objectives, hypotheses, and variables

The objectives of this study were to (i) investigate the effect of combined lag on manual discrete tracking task in a virtual environment, (ii) determine the interaction between the hand and head-related lag, and (iii) model the performance of discrete manual task in the presence of lags. The hypotheses were:

(i) hand movement time will increase with increasing hand-related lag,

(ii) using a constant lag, the relationship among movement time, target width, and target distance will obey Fitts' law,

(iii) with the existence of head-related lag, the movement time will increase with the increasing r.m.s. head movement,

(iv) lag will have no significant interaction with target distance, and

(v) lag will have a significant interaction with the effects of target width.

The latter two hypotheses were based on the findings of Experiment 2 and a recent study concerning the effects of head movement related lag (So *et al.,* 1999). The dependent variables were r.m.s. head movement, hand movement time, and hand reaction time. In this experiment, target width (2cm 4cm), target distance (14cm 18cm 24cm 54cm 62cm 70cm), imposed head-related lag (0ms 110ms 220ms), and imposed hand-related lag (0ms 110ms 220ms) were manipulated. The base lag of the experimental environment was 55 ms.

7.3 Task, procedure, and participants

Subjects were asked to hit a target square as fast as possible using the index finger of the virtual hand. When the square was hit, the color of the square changed and the finger needed to stay on the target for two frames (i.e., about 110 ms) until the target square disappeared. A target capturing criteria used in previous studies (Jagacinski and Monk, 1985; So *et al.*, 1999) were adopted. The virtual world was spatially calibrated to carefully match with the real world, so that when the subjects were pressing on a table in Virtual

Environment, they were also pressing on a table in the real world. This ensured that the subjects would have tactile feedback.

At the beginning of the experiment, a detailed explanation of the task was given to the subjects. After that, there was a series of practice tasks without lag so that the subjects became familiarized with the virtual world, the apparatus and the task requirement. This was followed by 9 conditions exhausting the 9 combinations of hand and head-related lags. Each condition had 12 runs exhausting the 12 combinations of target distances and target widths. The order of presenting the runs and conditions was randomized. Each condition was repeated 4 times. There was a one-minute rest between each condition.

Twelve healthy males aged between 19 to 40 participated in this experiment. They were paid HK$70 as a compensation for their time.

7.4 Results

An ANOVA was conducted on hand movement time data collected. A significant effect of replications was found ($F_{3,4952}$=35.59, p<0.0001). The mean hand movement times with the four replications are illustrated in Figure 7-1. As shown in the figure, the mean performance improved during the first replications and this improvement flattened out during the second, third and fourth replications.

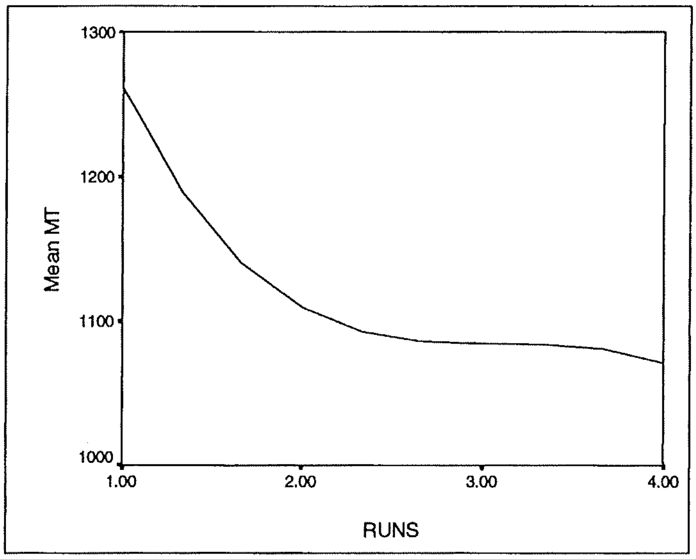

Figure 7-1: Plot of the effects of practices, MT vs Replication (Practice).

After the first replications were excluded from the ANOVA analysis (Table 7-1), the effect of replication was no longer significant ($F_{2,3678}$=2.18, p<0.1135). As a result, the data from the first replication was excluded in all of the subsequent analyses.

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Hand Lag	2	194.924941	97.462470	418.48	0.0001
Head Lag	2	23.969408	11.984704	51.46	0.0001
Subject	11	164.526942	14.956995	64.22	0.0001
Replication	2	1.014397	0.507199	2.18	0.1134
ID	11	366.196323	33.290575	142.94	0.0001
Head Lag * Hand Lag	4	5.505961	1.376490	5.91	0.0001
Head Lag * ID	22	10.568112	0.480369	2.06	0.0025
Head Lag * Subject	22	20.465204	0.930237	3.99	0.0001
Head Lag * Replication	4	0.994714	0.248679	1.07	0.3707
Hand Lag * ID	22	6.118543	0.278116	1.19	0.2412
Hand Lag * Subject	22	19.431554	0.883252	3.79	0.0001
Hand Lag * Replication	4	1.131823	0.282956	1.21	0.3022
Subject * ID	121	65.151515	0.538442	2.31	0.0001
Error	3637	847.050136	0.232898		
Corrected Total	3886	1727.049573			

Table 7-1: ANOVA table on hand movement time (excluded first replication)

Following the traditional way of analysis by Hoffmann (1992), an ANOVA was conducted using hand-related lag, head-related lag, subject, replication, and

ID as the factors. The ANOVA results (Table 7-1) indicated that the hand-related lag, head-related lag, ID and subject all had a significant effect on the hand movement time (MT). (hand-related lag: $F_{2,3637}$=418.48, *p*<0.0001; head-related lag: $F_{2,3637}$=51.46, *p*<0.0001; ID: $F_{11,3637}$=142.94, p<0.0001; Subject: $F_{11,3637}$=64.22, *p*<0.0001). The two-level interaction effect were significant between: hand and head-related lag ($F_{4,3637}$=5.91, *p*<0.0001), head-related lag and ID ($F_{22,3637}$=2.06, *p*<0.0025), head-related lag and subject ($F_{22,3637}$=3.99, *p*<0.0001), hand-related lag and subject ($F_{22,3637}$=3.79, *p*<0.0001), subject and ID ($F_{121,3637}$=2.31, *p*<0.0001). The interaction between hand-related lag and the ID was insignificant. This was different from the study of Hoffmann(1992), in which they proposed a interaction relationship between the time lag and the ID.

Source	DF	Anova SS	Mean Square	F Value	Pr > F
Hand Lag	2	194.924941	97.462470	416.64	0.0001
Head Lag	2	23.969408	11.984704	51.23	0.0001
Subject	11	164.526942	14.956995	63.94	0.0001
Replication	2	1.014397	0.507199	2.17	0.1145
Width	1	48.968936	48.968936	209.34	0.0001
Distance	5	314.331548	62.866310	268.74	0.0001
Head Lag * Hand Lag	4	5.505961	1.376490	5.88	0.0001
Head Lag * Width	2	0.031923	0.015961	0.07	0.9340
Head Lag * Distance	10	5.370517	0.537052	2.30	0.0111
Head Lag * Subject	22	20.465204	0.930237	3.98	0.0001
Head Lag * Replication	4	0.994714	0.248679	1.06	0.3731
Hand Lag * Width	2	1.961553	0.980776	4.19	0.0152
Hand Lag * Distance	10	2.682171	0.268217	1.15	0.3228
Hand Lag * Subject	22	19.431554	0.883252	3.78	0.0001
Hand Lag * Replication	4	1.131823	0.282956	1.21	0.3045
Subject * Width	11	3.128434	0.284403	1.22	0.2701
Subject * Distance	55	47.380191	0.861458	3.68	0.0001
Distance * Width	5	2.895840	0.579168	2.48	0.0301
Error	3712	868.333516	0.233926		
Corrected Total	3886	1727.049573			

Table 7-2: ANOVA table on hand movement time (excluded the first replications)

Upon inspection the interaction among hand-related lag, target distance and the target width, may be different from the interaction between the hand-related lag and ID. The "index-of-difficulty" was divided into target distance and target width. The ANOVA results (Table 7-2) showed that the hand-related lag, head-related lag, target width, target distance, and subject all had a significant effect on hand Movement Time (MT) (hand-related lag: $F_{2,3712}$=416.64, p<0.0001; head-related lag: $F_{2,3712}$=51.23, p<0.0001; Target Width: $F_{1,3712}$=209.34; Target Distance: $F_{5,3712}$=268.74, p<0.0001; Subject: $F_{11,3712}$=63.94, p<0.0001). The two-level interaction effect was significant between: hand and head-related lag ($F_{4,3712}$=5.88, p<0.0001), head-related lag and target distance ($F_{10,3712}$=2.30, p<0.0111), head-related lag and subject ($F_{22,3712}$=3.98, p<0.0001), hand-related lag and target width ($F_{2,3712}$=4.19, p<0.0152), hand-related lag and subject ($F_{22,3712}$=3.78, p<0.0001), subject and target distance ($F_{55,3712}$=3.68, p<0.0001), target distance and width ($F_{5,3712}$=2.48, p<0.0301).

It is important to note that there was no significant interaction between hand-related lag and target distance ($F_{10,3712}$=1.15, p>0.3228). This result agrees with the previous experiment on the effect of hand-related lag on manual discrete task.

The target distances can be divided into two groups, inside, and outside field-of-view (FOV). With the distances inside FOV, the subjects can look at both starting and finishing pad at the same time without moving their head. Figure 7-2 shown the r.m.s. head yaw movement versus the different target distances. There is a big step on the head movement, at the point between the inside and outside FOV distances. At the beginning of each task the subjects were asked to look at the position of both starting and finishing pads. When both starting and finishing pads were inside FOV, they can adjust their head position to look at both starting and finishing pad at the same time. Therefore, head movement shown a lot of differences when the target distances in inside or outside FOV.

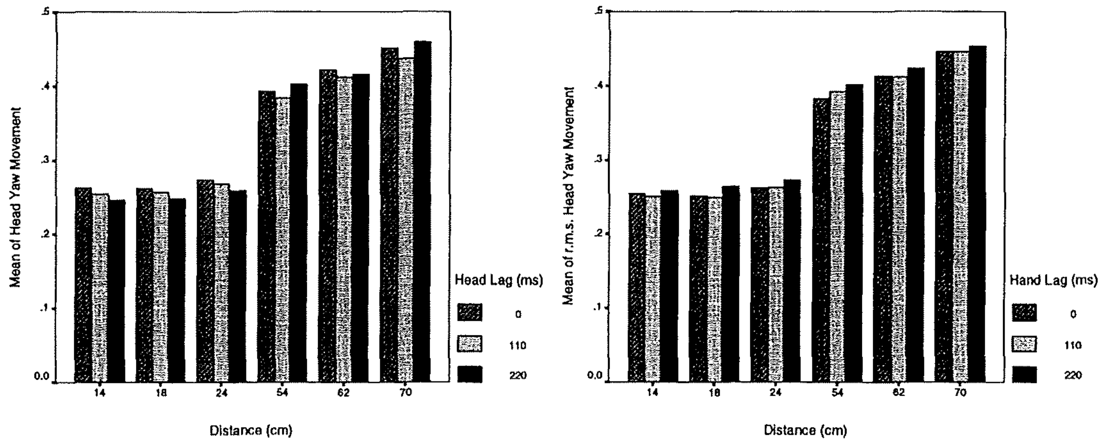

Figure 7-2: r.m.s. Head movements (Yaw) in different target distances

The ANOVA tables shown in the next page were the ANOVA analysis at the target distances 14 and 18 cm. The interaction between the hand-related lag and target width was disappeared at the target distance at 14 cm. At target distance 18 cm the interaction appear again however.

Source	DF	Anova SS	Mean Square	F-Value	Pr>F
Hand Lag	2	29.7489184	14.8744592	54.06	0.0001
Head Lag	2	1.6348556	0.8174278	2.97	0.0521
Subject	11	20.9961259	1.9087387	6.94	0.0001
Runs	2	0.2387504	0.1193752	0.43	0.6482
Width	1	2.6026428	2.6026428	9.46	0.0022
Hand lag * Head lag	4	1.0475986	0.2618997	0.95	0.4336
Head lag * Width	2	0.7859901	0.3929951	1.43	0.2406
Head lag * Subject	22	14.6447040	0.6656684	2.42	0.0003
Head lag * Runs	4	2.9927327	0.7481832	2.72	0.0290
Hand lag * Width	2	0.2073277	0.1036638	0.38	0.6863
Hand lag * Runs	4	0.7938710	0.1984677	0.72	0.5776
Hand lag * Subject	22	9.4817614	0.4309892	1.57	0.0488
Width * Subject	11	3.0593821	0.2781256	1.01	0.4351
Error	557	153.2693641	0.2751694		
Corrected Total	646	241.5040248			

Table 7-3: ANOVA table on hand movement time (At Distance = 14cm) (excluded the first replications)

Source	DF	Anova SS	Mean Square	F-Value	Pr>F
Hand Lag	2	40.3098542	20.1549271	124.06	0.0001
Head Lag	2	2.5945198	1.2972599	7.99	0.0004
Subject	11	28.8457855	2.6223441	16.14	0.0001
Runs	2	0.2439326	0.1219663	0.75	0.4725
Width	1	6.1789543	6.1789543	38.03	0.0001
Hand lag * Head lag	4	0.4074833	0.1018708	0.63	0.6434
Head lag * Width	2	0.0974667	0.0487334	0.30	0.7410
Head lag * Subject	22	10.1354241	0.4607011	2.84	0.0001
Head lag * Runs	4	0.5511683	0.1377921	0.85	0.4950
Hand lag * Width	2	1.7407322	0.8703661	5.36	0.0050
Hand lag * Runs	4	0.9619467	0.2404867	1.48	0.2067
Hand lag * Subject	22	6.4334877	0.2924313	1.80	0.0143
Width * Subject	11	1.6311965	0.1482906	0.91	0.5276
Error	558	90.650629	0.162456		
Corrected Total	647	190.782581			

Table 7-4: ANOVA table on hand movement time (At Distance = 18cm) (excluded the first replications)

7.5 Discussion

The significant effect of the hand-related lag in this experiment agreed with the previous experiment (pure hand-related lag experiment). The delayed visual feedback caused the inaccuracy of the first ballistics movement, which increased the task completion time.

According to Fitts' Law, movement time was significantly affected by index-of-difficulty ($ID=\log_2 2*D/\log_2 W$). Fitts' Law proved to be applicable in Virtual Environment from the previous studies (Ware *et al.*, 1994b). Therefore both distance and target width are significant in this experiment.

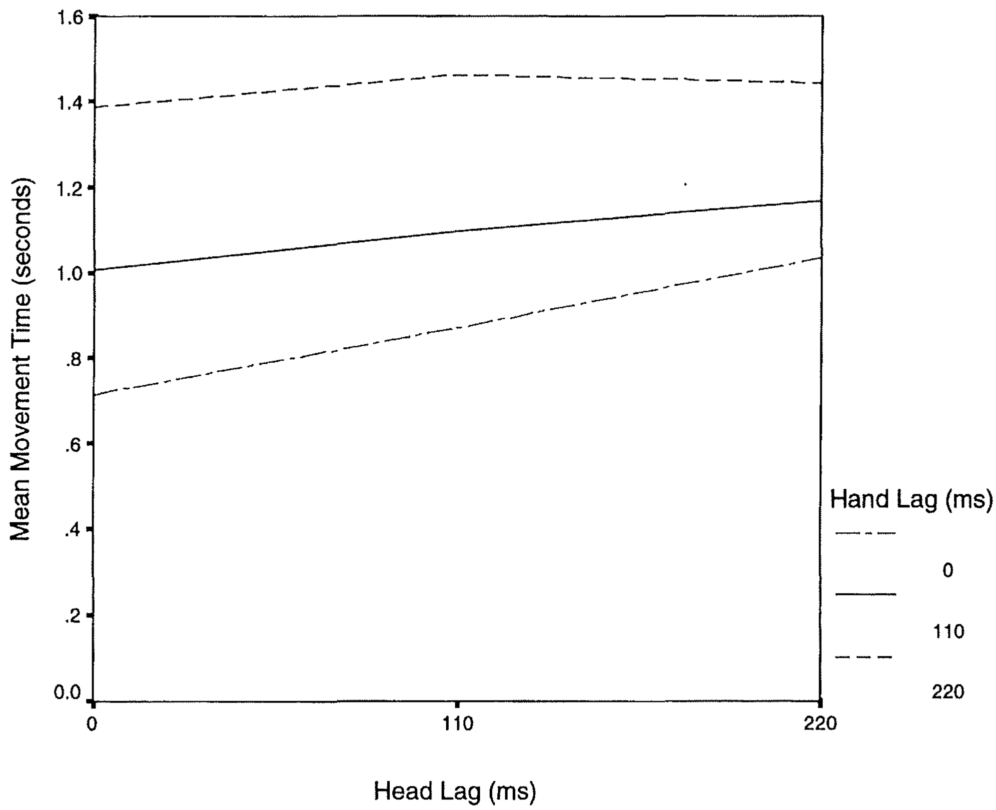

Figure 7-3: Interaction plot between hand and head-related lag

Figure 7-3 shown a negative interaction between the hand and head-related lag. When head-related lag was increased, then the effect of the hand-related lag on the hand movement time was decreased and vice versa.

	Movement Time (seconds)			
Hand Lag (ms)	Head Lag (ms) (The head lag is constant down the row)			MT Increased (Head Lag: 0-> 220 ms)
	0	110	220	(%)
0	0.714963	0.870488	1.034345	**44.67113**
110	1.008085	1.095279	1.168104	**15.87361**
220	1.38637	1.462282	1.44303	**4.086954**
MT increased (Hand Lag: 0-> 220 ms) (%)	**93.90793**	**67.98425**	**39.5115**	

Table 7-5: Means of the hand movement time in 9 lag conditions

Table 7-5 shows the averages of the hand movement time in 9 lag conditions. At a fixed head-related lag (0, 110, or 220 ms) the movement time increased by 93%, 68%, and 39% respectively, when the hand-related lag was increased from 0 to 220 ms. At a fixed hand-related lag (0, 110, or 220 ms) the movement time increased by 45%, 16%, and 4% respectively. It was reasonable to conclude that the effects of hand-related lag was more important than head-related lag.

7.5.1 Validate the proposed regression equation in experiment two (EHA_D)

In order to validate the regression model predicted from Chapter 6, a new variable (CMT) was generated using a method similar to that used in the previous experiment. The other variable (pCMT) was generated using the regression model to predict the change of the movement time of this experiment. CMT and pCMT were compared using paired sample t-test. The t-test result is shown in table 7-6 below.

Head Lag (ms)	T – Value	Df	Prob > ITI
0	-3.977	1151	0.0001
110	-0.354	1151	0.723
220	5.597	1149	0.0001
Mean	1.018	3453	0.3090

Table 7-6: Paired sample t-test result in different head lag condition

From the result of the t-test, it was found that there was no significant difference between the predicted change of movement time (pCMT) and the change of movement time (CMT) measured in this experiment. It was suggesting that the regression model developed from the last chapter could predict the change of the movement time effectively at 110 ms head-related lag condition. The predictions were not effective, when 0, and 220 ms head-related were exist, however, they were significant in opposition direction. Obviously, for the refinement of this prediction formula is needed. Nonetheless, these results indicate that the research is in the correct direction and future researches are desirable.

7.5.2 A model of the combined effects of hand and head-related lag

Up to now, the results of the three experiments (EP_D, EHA_D and EHA&HE_D) can be summarized as (i) effects of practice was significant but the effects dissipated after two practices; (ii) both head-related lag and hand-related lag significantly affected target-directed hand Movement Time (MT); (iii) the effects of the hand-related lag was greater than that of head-related lag; (iv) in the presence of constant lags, MT obeys the Fitts' law; (v) the effects of head-related lag had significant interactions with the effects of D but not W; (vi) the effects of hand-related lag had significant interactions with the effects of W but not D; and (vii) a pattern of movement has been identified for typical target-directed hand movements and this pattern can explain the significant interactions between the effects of hand-related lag and W and the lack of interaction between the effects of hand-related and D.

In the light of these findings, regression models to predicts target-directed hand Movement Time (MT) as functions of target width (W), target distance (D), head-related lags (L_{head}), and hand-related lags (L_{hand}) have been developed.

When the regression analyses were repeated for all the MT data obtained in Experiment 2 (EHA&D) (i.e., not restricted to the zero imposed head-related lag condition), the

Following regression equation was obtained:

$$MT = -0.8179 + 0.3096 \log_2(D) + 0.1421 \log_2(2/W) + 2.7244 (L_{hand}) + 0.4970 (L_{hand} \times \log_2(2/W)) \qquad R^2 = 0.8949 \quad (1)$$

According to Table 7-1, the effects of L_{head} had significant interactions with the effects of D but not W. As a consequent, the term 'L_{head}' and 'L_{head} x D' were added to the regression analyses and the results obtained are shown as follows:

$$MT = -0.6544 + 0.2496 \log_2(D) + 0.1422 \log_2(2/W) + 2.724 (L_{hand}) + 0.4967 (L_{hand} \times \log_2(2/W)) - 0.9899 (L_{head}) + 0.3636 (L_{head} \times \log_2(D)) \qquad R^2 = 0.9373 \quad (2)$$

Inspections of Equation (1) and (2) indicate that R^2 had increased back to 0.9373. This suggests that the 'L_{head}' and 'L_{head} x D' may be added to include the head-related lag (L_{head}) to the regression model.

Other than the interactions included in the above regression, from the ANOVA results it also shown that there was significant interaction between L_{hand} and L_{head}. Therefore, the data were further analyzed using stepwise regression . The terms, L_{hand}, L_{head}, W, D, L_{hand} * W, L_{hand} * D, L_{head} * W, L_{head} * D, and L_{head} * L_{hand} contributed in this stepwise regression analysis with the leaving and entry level at 0.05 significant level.

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F Value	Prob> ITI
Intercep	-0.8176	0.0547	65.7391	233.34	0.0001
L_{hand}	3.4684	0.2177	74.7012	253.79	0.0001
W	0.1423	0.0364	4.4958	15.27	0.0001
D	0.2573	0.0114	151.224	513.77	0.0001
L_{hand} * L_{head}	-4.5139	1.0256	5.7022	19.37	0.0001
L_{head} * D	0.3168	0.0374	21.0935	71.66	0.0001
L_{hand} * W	0.4963	0.1938	1.9304	6.56	0.0105

Table 7-7: Stepwise regression analysis results

Interestingly, the term $L_{head} * L_{hand}$ had negative estimated parameter, it was due to the significant negative interaction between the head and hand-related lag, which was shown in Figure 7-3.

L_{head} was picked out from the regression model, due to the insignificant level from the ANOR analysis. The reason of this insignificant is due to the effect of hand-related lag associated a lot with the target distance. Finally, we came up with this regression model.

$$\begin{aligned} MT = & -0.8176 + 3.4684\, L_{hand} + 0.1423 * Log_2(2/W) + 0.2573\, Log_2(D) \\ & - 4.5139\, L_{hand} * L_{head} + 0.3168\, L_{head} * Log_2(D) \\ & + 0.4963\, L_{hand} * Log_2(2/W) \qquad R^2 = 0.9449 \end{aligned}$$

The regression models, however, were formulated with the imposed time lag from 0 to 220ms, target width from 2 to 4 cm, and target distance from 14 to 70cm. Further research are needed to test the extensibility of the application of this model outside the specified ranges.

CHAPTER 8 Effects of combined hand and head related lags on continuous manual tracking performance (EHA&HE_C)

8.1 Introduction

In this chapter, an experiment studying the effects of combined lags on a continuous manual tracking task is presented. The effects of combined lags on continuous manual tracking task have been studied even though this task is very common in Virtual Reality (VR) applications. Examples of continuous manual tasks include target tracking, driving, and writing. Factors investigated in this experiment included practice, duration of head-related lag, and duration of hand-related lag.

8.2 Objectives and hypotheses

The objectives of this experiment were to: (i) investigate the effects of combined lags on a manual tracking task, and (ii) evaluate the individual role of hand and head-related lags on task performance degradation. It was hypothesised that:

i. as the hand-related lag increases, the tracking error would increase;
ii. as the head-related lag increases, the tracking error would increase.

These two hypothesizes were based on the results of previous experiments, that both head and hand-related lags could significantly affect the discrete manual task performance in a VR system.

8.3 Task, procedure, and participants

Twelve male University students aged between 19 to 24 participated as subjects in the experiment in which they performed a series of continuous target tracking task with their index finger's tip. Subjects of the same gender were used to eliminate the effects of gender variable. Each run lasted about one and a half minutes. At the start of each run, the subjects were asked to keep the tip of the virtual index finger on the target sphere (Figure 8-2).

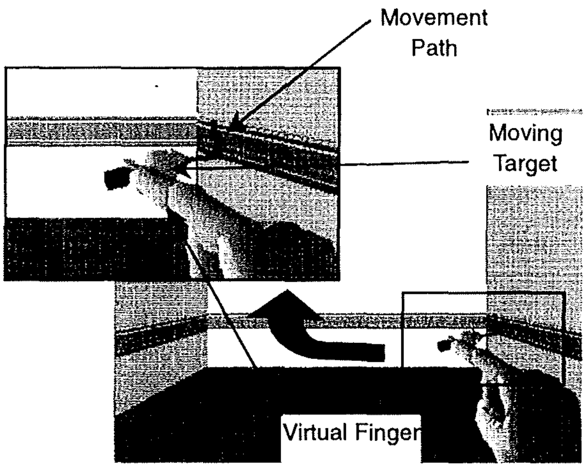

Figure 8-2: Snapshot of the task (the subject was tracking the moving target)

When the target started to move, the subjects were instructed to follow the target with their 'virtual' index finger tip as accurately as possible. When the tip of the virtual finger collided with the target, the target sphere was a light blue color; otherwise, it was in light red color. Written instructions were given to the subjects before the experiment and each subject was given a training session on the tracking task and the use of the Cooper-Harper rating scale for assessing the task difficulty. Six practice training runs were followed by 2 repetitions of 15 runs. The 15 runs exhausted the combinations of three head-related lags (0, 220, 440ms), and five hand-related lags (0, 55, 110, 220, and 440ms). There was a rest between each run. More levels of hand-related lags were used because previous experiments (EHA&HE_D) had shown that the effects of hand-related lags were greater than that of head-related lag. The target movements in three axes (vertical, lateral, and fore-aft) were extracted from the same band limited random target function. This was done to ensure that the frequency contents of the target movements in the three axes were the same. In order to make the three target movements appeared to be different, they were started at different points. The three target functions are shown in Figure 8-3 as functions of points (each point is separated by 55ms). For example, an initial target position can be chosen as the 400th point, 1050th point, and 0th point on the lateral, vertical, and fore-and-aft target functions. As the target moved, the future target position would seem be the next point of the target functions. An inspection of Figure 8-3 indicate that all three target functions can be joined end-to-end so that there would be a smooth transition as the target moved from the last point to the first point of a target function. All in all, this arrangement enabled the presentation of a randomly moving target in a 3D space with the same frequency content at all three directions. As shown in Figure 8-3, the target functions in the three axes had been scaled to fit a target span window of ±28cm (lateral), ±19cm(vertical), and ±8cm(fore-and-aft). This window was used based on the anthropometric data of Hong Kong male population. The target functions were generated from a random function, integrated once and low-passed at 0.8Hz. These functions had been carefully selected, so that they were easy to track in the absence of imposed lag (i.e. time-on-target > 75%). Preliminary test runs were also performed to ensure a high coherence (>0.7) up to 0.5Hz. The duration of the target function was 1.5 minutes and the sample period was 55 ms.

All subjects were given written instructions about the purpose and methods of the experiment. Their written consents were obtained before the experiment.

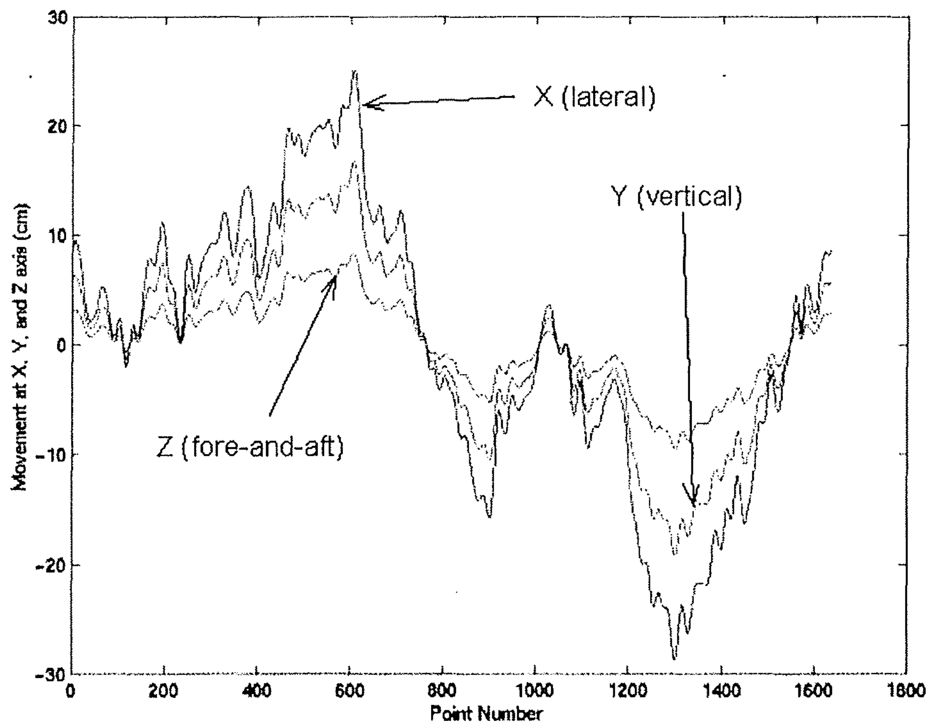

Figure 8-3: X (lateral), Y (up-and-down) and Z (fore-and-aft) axis Target Function

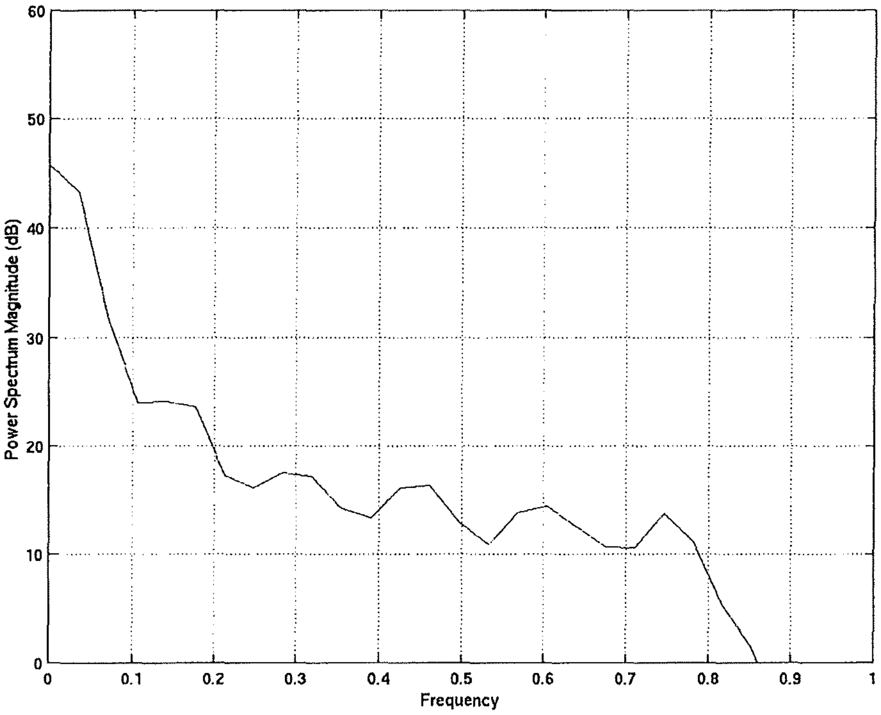

Figure 8-4: Power Spectral Density of the target function

8.4 Results

An ANOVA was performed to determine the effects of repeated results. This analysis indicated that r.m.s. tracking errors were not significantly affected by repeated runs during both the training ($F_{2,69}$=0.19, p>0.8292) and also the main experiment ($F_{1,250}$=0.56, p<0.4537) (Table 8-1, 8-3). Further analysis indicated that sequence (at practice run - 0, at main experiment - 1) and repeats (3 practices runs and 2 main experiment runs) had no significant effect on r.m.s. tracking errors (Table 8-2) in the lag conditions (Hand Lag - 0ms Head lag - 0ms & Hand Lag - 440ms Head Lag - 440ms).

Source	Df	Sum of Square	Mean Square	F-Value	Pr > F
Replication	2	1.02445316	0.51222658	0.19	0.8269
Error	69	185.44264841	2.68757461		

Table 8-1: ANOVA table on the effect of practice during practice runs

Source	Df	Sum of Square	Mean Square	F-Value	Pr > F
Replication	4	6.36895281	1.59223820	0.67	0.6110
Sequence	1	5.27013838	5.27013838	2.23	0.1379
Error	114	269.0955397	2.3604872		

Table 8-2: ANOVA table on the effect of repeats and sequence across the practice runs and main experiment (Head Lag - 0ms Head Lag - 0ms and Hand Lag - 440 ms Head Lag - 440ms)

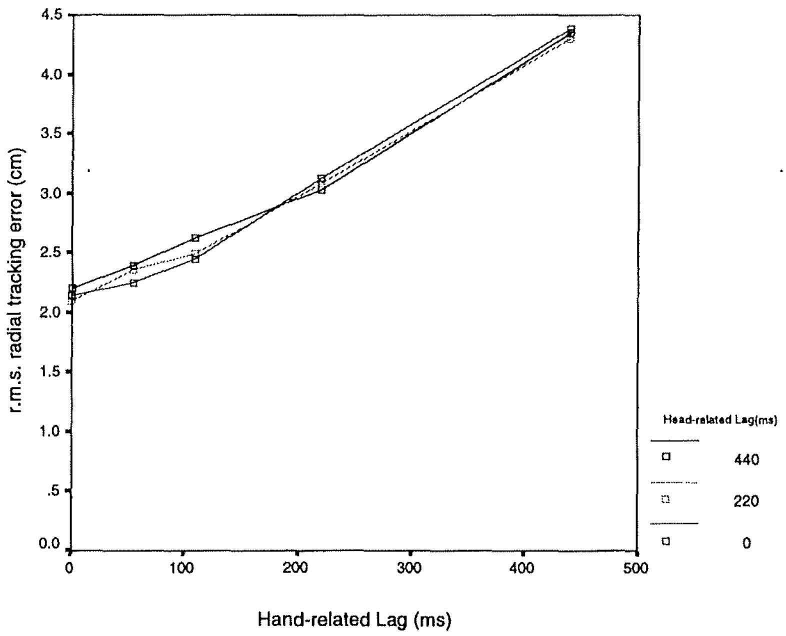

Figure 8-5: r.m.s. radial tracking errors on different hand and head related lag situations

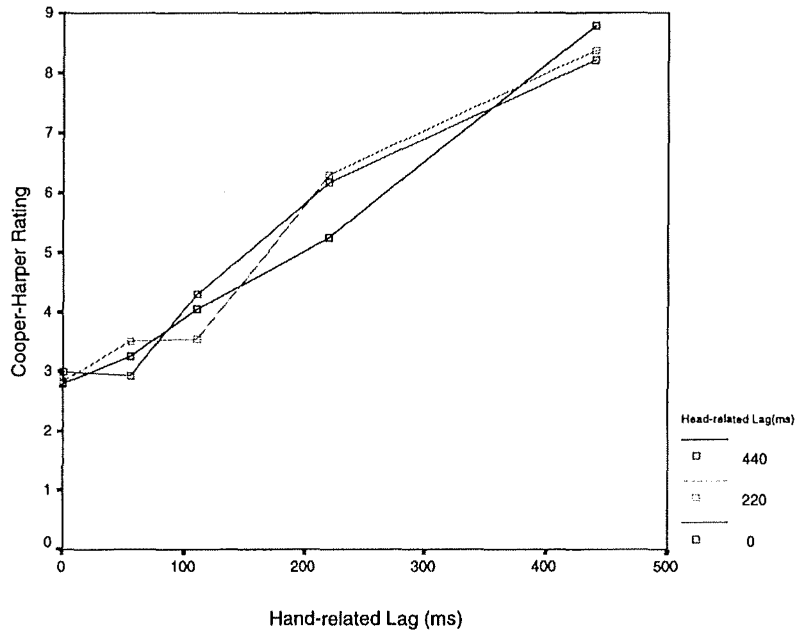

Figure 8-6: Cooper-Harper rating on different hand and head related lag situations

Results of an ANOVA (Table 8-3) and the Figure 8-4 indicated that (i) r.m.s. tracking errors were significantly affected by hand-related lag ($F_{4,250}$=614.18, *p*<0.0001) only; (ii) the head-related lag had no significant effect on the r.m.s. tracking errors ($F_{2,250}$=1.21, p>0.3009); and (iii) there was no significant interaction between the effects of head-related lag and the effects of hand-related lag. These findings support the first hypothesis of this experiment: (i) as the hand-related lag increases, the r.m.s. tracking error increases; however, it disagrees the second hypothesis (ii) as the head-related lag increases, the r.m.s. tracking error increases (see Discussion section).

Source	Df	Sum of Square	Mean Square	F-Value	Pr > F
Subject	11	131.145960	11.922360	128.73	0.0001
Hand Lag	4	227.523155	56.880789	614.18	0.0001
Head Lag	2	0.223528	0.111764	1.21	0.3009
Replication	1	0.052156	0.052156	0.56	0.4537
Hand Lag * Head Lag	8	0.825929	0.103241	1.11	0.3536
Subject * Replication	11	1.275257	0.115932	1.25	0.2534
Subject * Hand Lag	44	25.082391	0.570054	6.16	0.0001
Subject * Head Lag	22	3.034360	0.137925	1.49	0.0774
Hand Lag * Replication	4	0.218136	0.054534	0.59	0.6710
Head Lag * Replication	2	0.068969	0.034484	0.37	0.6895
Error	250	23.153125	0.092612		

Table 8-3: ANOVA table on the r.m.s. tracking error

Another ANOVA on the subjective ratings (Cooper-Harper rating) (Table 8-4) indicated that (i) Cooper-Harper rating was significantly affected by hand-related lag ($F_{4,250}$=265.6, p<0.0001). It is important to notice that Cooper-Harper rating was not significantly affected by head-related lag ($F_{2,250}$=0.21, p>0.8092) also, which was similar with the results found in the r.m.s. tracking error analysis.

Source	Df	Sum of Square	Mean Square	F-Value	Pr > F
Subject	11	643.16667	58.46970	40.19	0.0001
Hand Lag	4	1545.71111	386.42778	265.60	0.0001
Head Lag	2	0.61667	0.30833	0.21	0.8092
Replication	1	0.90000	0.90000	0.62	0.4323
Hand Lag * Head Lag	8	30.93889	3.86736	2.66	0.0081
Subject * Replication	11	15.96667	1.45152	1.00	0.4490
Subject * Hand Lag	44	199.55556	4.53535	3.12	0.0001
Subject * Head Lag	22	68.31667	3.10530	2.13	0.0029
Hand Lag * Replication	4	16.04444	4.01111	2.76	0.0285
Head Lag * Replication	2	0.15000	0.07500	0.05	0.9498
Error	250	363.73333	1.45493		

Table 8-4: ANOVA table on the Cooper-Harper rating

SNK Grouping	Mean	Hand Lag	SNK Grouping	Mean	Hand Lag
A	4.34410	440	A	8.4583	440
B	3.08156	220	B	5.9028	220
C	2.51801	110	C	3.9583	110
D	2.33069	55	D	3.2222	55
E	2.14303	0	D	2.8750	0

Table 8-5: SNK Grouping of Hand Lag on r.m.s. Tracking Error (Left), on Cooper Harper Rating (Right)

The SNK results of hand-related lag on r.m.s. tracking error and Cooper-Harper rating suggested that there is significant performance degradation at 55 ms hand-related lag, although there is no significant subjective difference between 0 and 55 ms hand-related lags.

A correlation analysis was also conducted among all the variables (Table 8-5). There were significant correlation between r.m.s. Error & Hand-related Lag, Hand-related Lag & Cooper-Harper Rating, and r.m.s. Error & Cooper-Harper Rating. This suggests that Cooper-Harper rating was closely related to the task performance. Ellis *et al.* (1997b) had also reported the performance was significantly correlated with the Cooper-Harper rating.

	Hand Lag	Head Lag	Replication	r.m.s. Error	Cooper-Harper Rating
Hand Lag	1.00000 0.0	0.00000 1.0000	0.00000 1.0000	0.73933 0.0001	0.72852 0.0001
Head Lag	0.00000 1.0000	1.00000 0.0	0.00000 1.0000	0.01883 0.7218	-0.01322 0.8026
Replication	0.00000 1.0000	0.00000 1.0000	1.00000 0.0	-0.01124 0.8316	-0.01766 0.7384
r.m.s. Error	0.73933 0.0001	0.01883 0.7218	-0.01124 0.8316	1.00000 0.0	0.75617 0.0001
Cooper-Harper Rating	0.72852 0.0001	-0.01322 0.8026	-0.01766 0.7384	0.75617 0.0001	1.00000 0.0

Table 8-6: Correlation analysis of all variables

Frequency domain analyzes were conducted on the movement of the target and the index finger tip. The transfer functions between the input (target movement) and the output (index finger tip's movement) were calculated, and presented as the magnitude and phase angle plots (Figure 8-7, 8-8, and 8-9).

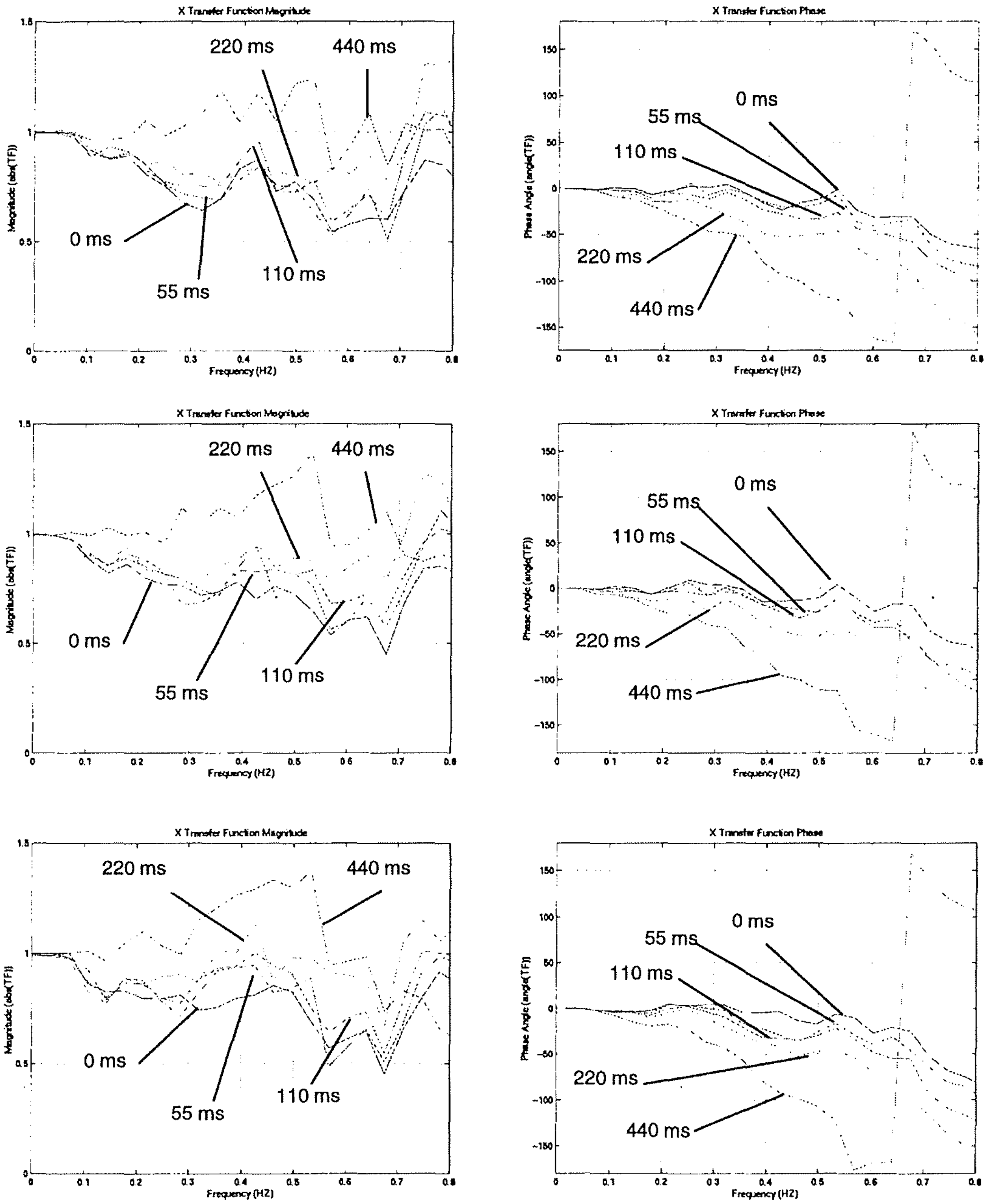

Figure 8-7: Mean hand tracking transfer function in the X (lateral) axis with different hand lags and constant head lag
(top - head lag fixed at 0 ms, middle - head lag fixed at 220 ms,
bottom - head lag fixed at 440ms, total 15 lag conditions presented)

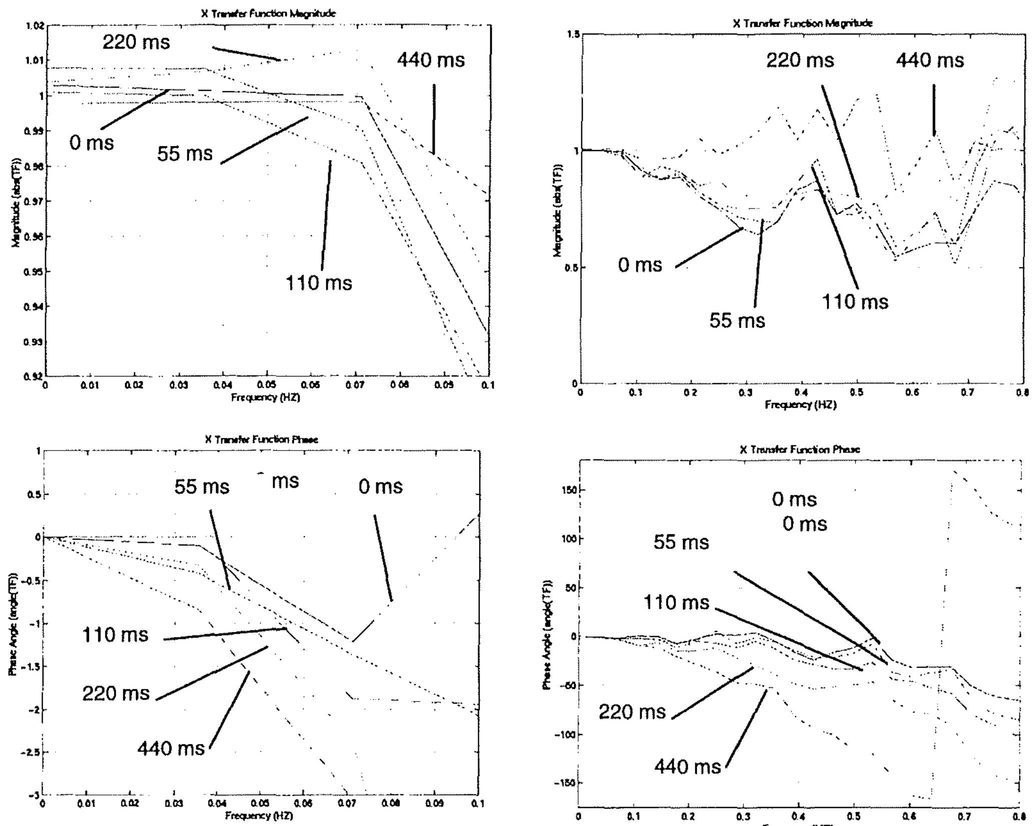

Figure 8-8: Mean hand tracking transfer function in the X (lateral) axis with different hand lags and constant head lag (Right). An enlarged figure on 0 – 0.1 Hz (Left)

Figure 8-7 describes the hand tracking characteristics at lateral axis in the presence of hand-related lag. With the constant head-related lag, there was an obvious pattern between the increase of hand-related lag, increased the hand tracking phase lags and gains. This frequency domain behavioral analysis result consistent with the statistical finding, that hand-related had significant effects on the task performance (r.m.s. Tracking error). The power spectral densities of the lateral axis tracking error with different hand-related lags and 0 ms head-related lag is shown in Figure 8-10. An inspection of the figure shows that as head-related lags increased the tracking error at lateral axis also increased. From the selected hand-related lag condition (0, 440 ms) in Figure 8-9, both gains and the phase lags did not change greatly, with the increases of the head-related lag (0 -> 440 ms).

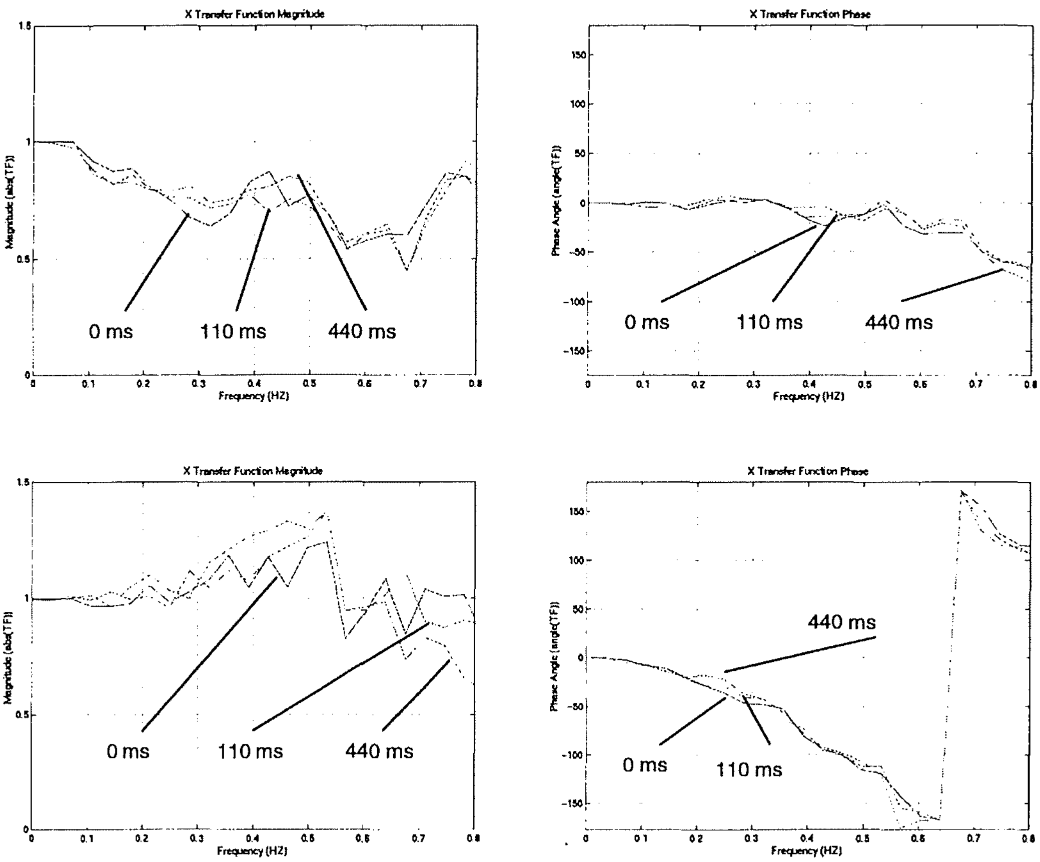

Figure 8-9: Mean hand tracking transfer function in the X (lateral) axis with different head lags and constant hand lag
(top - hand lag fixed at 0 ms, bottom - hand lag fixed at 440ms, total 6 lag conditions presented)

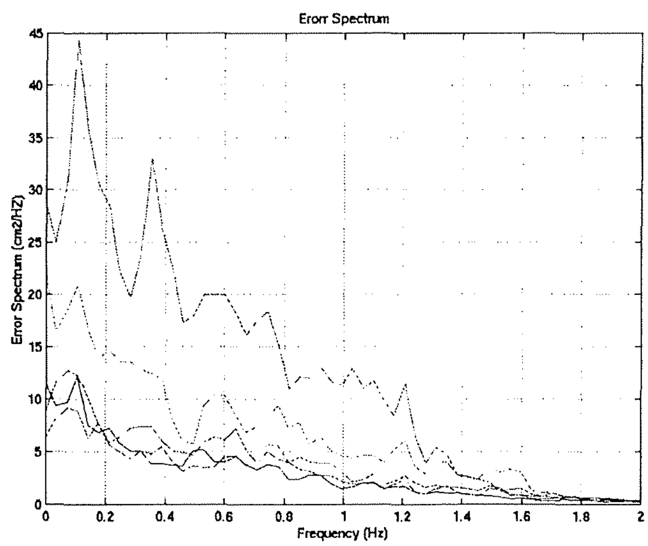

Figure 8-10: Power spectral densities of the lateral axis tracking error with different hand-related lags and 0ms head-related lag

8.5 Discussion

Ellis *et al.* (1997b) had conducted a similar study on the effects of time lag in a generic 3D manual tracking task. They found that time lag had significant effects on the tracking performance (r.m.s. Error).

Different from Ellis *et al.* study, in this experiment, time lags were divided into two different types, hand-related, and head-related lag. Following the findings of the previous experiments and the study (Ellis *et al.*, 1997b), it was hypothesised that (i) as the hand-related lag increases, the tracking error will increase; (ii) as the head-related lag increases, the tracking error will increase. The results confirmed the first hypothesis on hand-related lag, however, it disproved the second hypothesis in that the head-related lag did not have a significant effect on the manual tracking task performance. Results of the subjective Cooper-Harper rating also indicated that the Cooper-Harper ratings were not significantly affected by changes of head-related lags. In other words, head-related lag did not affect both the objective task performance (i.e. r.m.s. error) and subjective task performance (i.e. Cooper-Harper Ratings). In the frequency domain analysis the tracking pattern changed with the increase hand-related lags, but not with an increase of the head-related lags. At this point, it seems reasonable to conclude that head-related lags up to 440ms could not significantly affect a continuous manual tracking task performance. A possible reason of this insignificant effect might have been due to the indirect contribution of head-related lag. The subjects were using their fingers to track the targets, therefore, head movement was not directly involved in the finger tracking process task. On the other hand, hand-related lags affected the finger movement and, hence, performance directly. The head movement was required when the subjects tried to keep the virtual hand and target inside their views. In this task, the required head movements were relatively few, so this indirect effect did not significantly affect the task performance.

8.6 Conclusion

Manual tracking performance was significantly degraded by imposed hand-related lag. It did not appear in imposed head-related lag however. The tracking strategy also changed with an increase in hand-related lag. Cooper-Harper rating had a significant correlation with the task performance. The subjects closely related the controllability with the performance that they can achieve. With this significant correlation, the hand-related lag significantly affected the Cooper-Harper rating. The head-related lag did not significantly affect the Cooper-Harper rating.

The findings of this chapter filled in the last gaps of the present studies, as presented in Chapter 4. This comprehensive knowledge of the effects of hand and head-related lag in task performance could enable a better understand and solution for the problem of lags in Virtual Environment.

Further research is required to analysis how could the subjects behave in different time lag conditions and to study the effect of the head-related lag in different target velocities. In order to investigate thoroughly the effects of head-related lag a task with substantial head movements is required.

Chapter 9 Discussions, Conclusions and recommendations

9.1 Summary of experimental findings

In this thesis, results of four experiments are presented. They have been conducted to investigate the effects of hand and head-related lags on discrete and continuous task performance. The specific findings of the four experiments are summarized as follows:

(i) Imposed head-related lags greater than 110ms had significant effects on manual discrete task performance (lags were imposed on a base lag of 55ms). However, imposed head-related lags of magnitude up to 440 had no significant effects on continuous manual tracking task performance.

(ii) Imposed hand-related lags greater than 55ms had significant effects on both discrete and continuous manual task performance (lags were imposed on a base lag of 55ms).

(iii) With manual task performance in a Virtual Environment (VE) with lags, a hand-related lag had a significantly greater degrading effect than a head-related lag of the same magnitude.

(iv) For the discrete tasks, the increases in discrete target-directed hand Movement Time (MT) caused by hand-related lag increased with decreasing target width but were independent of changes in target distance.

(v) With a constant combination of head and hand-related lags, discrete target-directed hand movement times (MT) obey Fitts' law ($R^2 > 0.8$).

(vi) A modification of Fitts' law to include the effects of hand-related lags on discrete target-directed hand movement time (MT) has been developed ($R^2 > 0.9$).

(vii) A modification of Fitts' law to include the combined effects of head and hand-related lags on discrete target-directed hand movement time (MT) has been develop ($R^2 > 0.9$).

(viii) With continuous manual tracking tasks in a VE, tracking strategies (as measured by hand tracking transfer functions' gains and phases) changed with increasing hand-related lags.

(ix) With continuous manual tracking tasks in a VE, Cooper-Harper ratings significantly correlated with the r.m.s. tracking error. This the controllability was closely related to the task performance.

(x) With discrete manual control tasks, the effects of head-related lags had significant interactions with the effects of target distance but no with target width. Combining this finding with the 4th finding, it can be concluded that, in the presence of lags, the effects of target width and target distance should not be analyzed as a single combined effect of "Index-of-Difficulty".

9.2 Quantitative models to predict the effects of lags on discrete manual task performance in a VR system

9.2.1 Predicting the effects of hand-related lag

In this thesis, a regression model has been developed to predict the changes of the task performance with different imposed hand-related lags. The model developed is shown here:

$$CMT(lag) = 2.304 * lag + 0.969 * [lag * \log_2(2/W)]$$

$R^2 = 0.96$

Where lag - hand-related lag

W - target width

CMT - Changes of hand movement time due to lags

This model has been developed based on the finding that there were significant interactions between hand-related lag and the target width, but not with target distance. The interaction between the target width and lag was included in a regression model (R^2>0.9). The ability of this model to predict the effects of hand-related lag has been tested in Experiment 3. There was no significant difference between the predicted hand movement time data and the measured hand movement time data.

9.2.2 Predicting the combined effects of hand and head-related lags

Based on the pattern of movement identified, and the findings of the first three experiments. Another regression model has been developed (see Chapter 7). A regression model to predict target-directed hand Movement Time (MT) as functions of target width (W), target distance (D), head-related lags (L_{head}), and hand-related lags (L_{hand}) have been proposed.

$$MT = -0.6544 + 0.2496 \log_2(D) + 0.1422 \log_2(2/W) + 2.724 (L_{hand}) + 0.4967 (L_{hand} \times \log_2(2/W)) - 0.9899 (L_{head}) + 0.3636 (L_{head} \times \log_2(D)) \qquad R^2 = 0.9373$$

This model suggests an interaction between the effect of L_{hand} and W and an interaction between L_{head} and D. These are important findings for the Virtual Reality systems design engineers. For example, a Virtual Reality application that requires large amount of the precise movement in a short range, based on these findings the design engineers should concentrate their resources to minimize the hand-related lag, rather than head-related lag in their Virtual Reality system. It is only a simple application of these findings of interactions. It is also important for the design of VR applications in which an optimal balance between the duration of hand and head-related lags are needed.

After all, can this study solve the problem of floating as mentioned inside the literature review of this study? The answer is yes or no, clearly it cannot solve this problem now with the results of this study, since the floating effect is due to the existing of the head-related lag, the method to minimize time lag is not the goal of this study. However, using the models and relationship found in this study, a better compensation algorithm can be formulated, so as to minimize the lag in a Virtual Reality system.

9.3 A qualitative explanation of the quantitative model of hand-related lags

The main characteristic of the quantitative model (i.e., the regression model stated in Section 9.2.1) are: (i) it does not contain 'Index-of-Difficulty, ID' as in the previous literature (e.g., MacKenzie and Ware, 1993 and Hoffmann, 1992); and (ii) it contains the multiplicative term between hand-related lag and target width. These characteristics were based on the statistical findings that the effects of hand-related lags had significant interactions with the effects of target width but not with target distance (see Chapter 6). A conceptual explanation of these interaction effects based on the patterns of target-directed hand movement have been offered (see Chapter 6). A typical of hand movement time history has been shown in Figure 6-4 and has been copied in Figure 9-1.

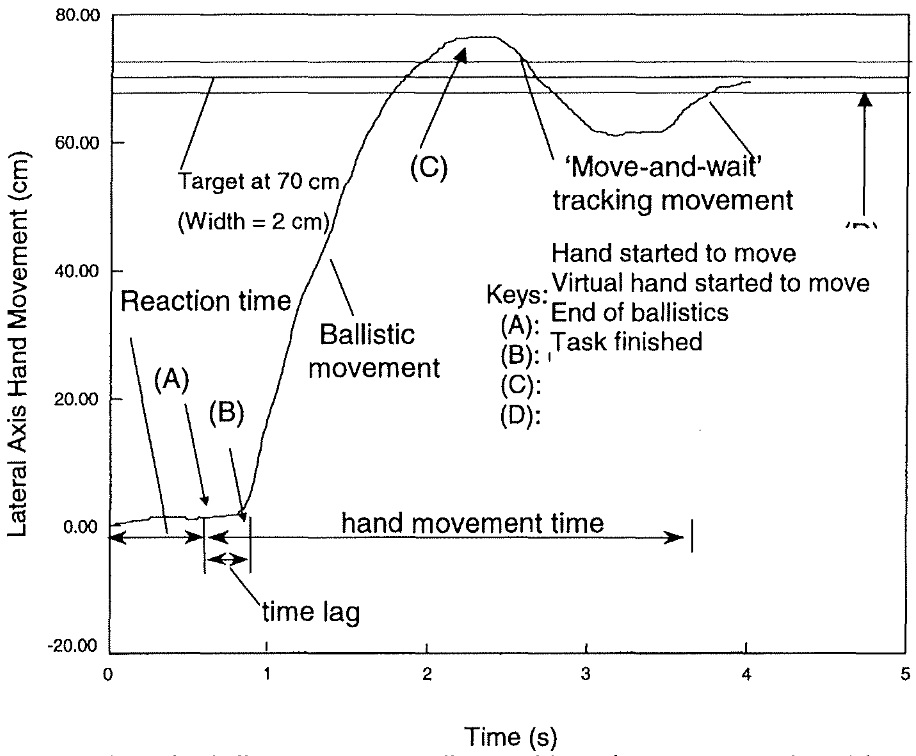

Figure 9-1 A typical discrete target-directed hand movement time history (copied from Figure 6-4).

Inspections of Figure 9-1 reveal two distinct stages of movements: (i) a projectile movement which brings the hand to the proximity of the target, and (ii) a series of compensatory tracking movements which bring the hand on top of the target. The second stage has been classified as compensatory tracking movements because the target is stationary in space. From the figure, it can be observed that the projectile movement is a smooth movement, which suggests that it is an open-loop feed-forward movement rather than a closed-loop feedback movement with continuous fine position adjustment. This observation is consistent with the comments from the subjects. Subjects were remembering the target position and when they were instructed to move, they projected their hands toward the "memorized" target position. In the absence of lag, this movement would have been enough to place the hands on top of the target. However, because of the hand-related lags, a series of compensatory tracking movements were needed. If the projectile movement was really a type of feed-forward movement based on the "memorized" target information (i.e., target distance and width), then the effects of hand-related lag would not be observable until the movement is over. In other words, the projectile movement (i.e., the first stage) will depend on the target distance and width but not the hand-related lag. For the second stage, as proved by the mathematics (see Chapter 6), the compensatory movement will depend on both the target width and hand-related lag but not target distance. When considering both the first and second stages, it is not difficult to see why the effects of hand-related lag will have significant interactions with target width and not with target distance.

According to the literature review in Chapter 3, the discovery of the two stages (i.e., the projectile and the compensatory tracking stages) is consistent with literatures on visual-motor behavior. Smith (1962) also reported that visual manual control movements have two types: (i) a transporting stage, and (ii) a positioning stage. The former refers to the large hand movement covering the low-frequency, predictable target movement while the latter refers to the fine and small positioning adjustments which places the hand on top of a moving target. In our case, the first stage can be classified as a type of predictable movement because the target is stationary. Because of the lag, the compensatory tracking is necessary which is very similar to the positioning stage as proposed by Smith (1962). In 1995, Guédon and his colleagues have proposed a model for describing visual motor control behavior (Figure 9-

2). In this model, the visual motor process has been divided into four parts: (i) the eye; (ii) the brain; (iii) the hand; and (iv) the experimental setup (i.e., the apparatus set-up). Within the brain, they further divide the manual operation into two types of controlling mechanisms: (i) a pre-program type feed-forward controlling mechanism (i.e., the 'Internal target trajectory representation' and 'Hand Controller Part II', and (ii) a fine tracking controlling mechanism (i.e., 'Hand Controller Part I'). This two type of controlling mechanisms are consistent with the two stages of movements that have been observed in this study. The 'projectile' feed-forward movement can be controlled by the pre-program type feed-forward mechanism while the 'compensatory tracking' movements can be controlled by the fine tracking controlling mechanism. The 'memorized' target information referred to in the subjects' comments is consistent with the 'Internal target trajectory representation'. Guédon *et al.* (1995)'s model has been modified to describe the visual-motor response in a Virtual Environment with lags (Figure 9-3).

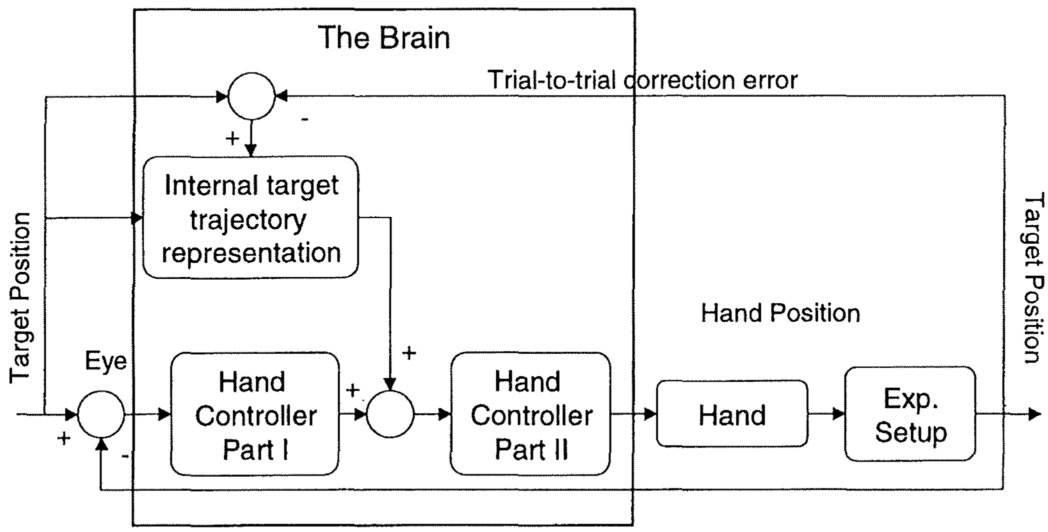

Figure 9-2 Visuo-manual system model (Guédon *et al.*, 1995)

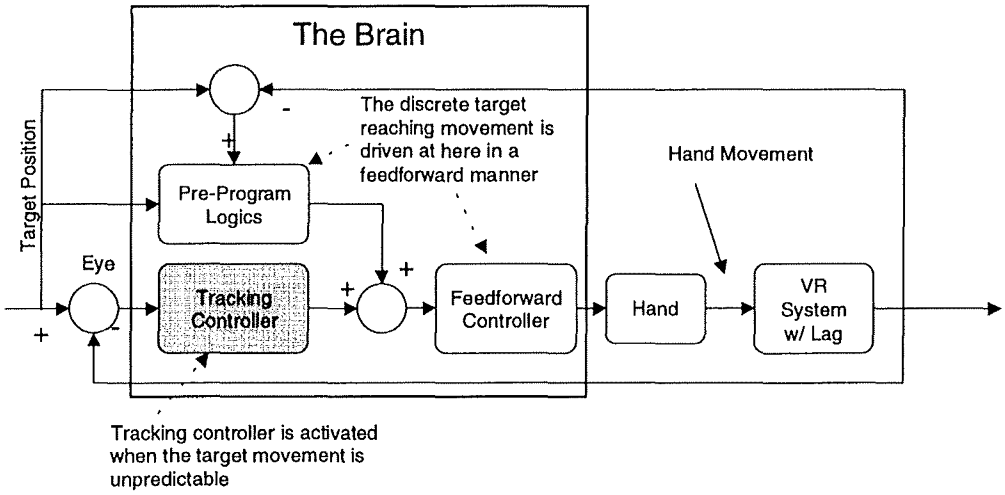

Figure 9-3: Visual-manual system model for VR system (modified from Model reported in Guédon *et al.*, 1995).

Using the conceptual model in Figure 9-3, the formation two stages of target-directed hand movement can be explained. Table 9-1 summaries the consistent comparison among our findings, Smith (1962)'s findings, and Guédon *et al.* (1995)'s findings.

Our Finding	Smith (1962)	Guédon et al. (1995)
Projectile	Transportation	Pre-programmed
Tracking	Positioning	Tracking

Table 9-1 Comparison the two stage movements finding among our finding, Smith (1962), and Guédon *et al.* (1995)

9.4 Conclusion

In this thesis, effects of hand and head-related lags in Virtual Environment have been studied. Hand-related lags greater than, or equal to, 55 ms or 110 ms imposed on a Virtual Reality system with 55 ms based lag can significantly affect both manual discrete and continuous task performance, respectively. However, the results indicate that imposed head-related lags up to 440 ms will not significantly affect the performance of a continuous manual task. With manual discrete task, imposed head-related lags greater than, or equal to, 110 ms can significantly degrade the performance.

In a manual discrete task, hand-related lag only has interaction with target width but not with target distance. Interestingly, head-related lag only has interaction with target distance but not with target width. These interaction effects are very important since the effects of target width and distance have always been treated as a single effect of Index-of-difficulty (ID) in the past literatures on effects of lags (e.g., MacKenzie and Ware, 1993, Hoffmann, 1992). The interactions are also useful for developing a model of the effects of lags. This thesis suggested that, in the presence of lags, ID should be analyzed as two individual terms ($\log_2$ (D), and $\log_2(2/W)$. Two regression models have proposed to predict the effects of hand-related lags ($R^2>0.9$) and the combined effects of hand and head-related lags ($R^2>0.9$) on discrete manual task performance. Using the model proposed for hand-related lag, the effects of hand-related lag in the third experiment have been successfully predicted. Suggestions on further refinement have also been presented.

A conceptual understanding behind the regression model of hand-related lag has been provided. This understanding have been shown to be consistent with the past literatures on visual motor behavior. This further convinces the findings of this thesis.

9.5 Future Work Recommendations

Further studies are suggested to refine and improve the two regression models proposed to predict the effects of hand-related lags and the effects of hand and head-related lags. The latter one should be tested to validate its accuracy in the prediction of the effects of lags in Virtual Environment.

Further analysis on the effects of lags on continuous manual tracking performance using tracking transfer functions is also suggested. This further study can enrich the understandings of the behaviors of the subject in a Virtual Environment with lag.

Both the quantitative model and the qualitative understanding enable the generation of a better lag compensation algorithm to enhance the task performance in a VE with lags. The development of such a compensation algorithm to enhance the task performance in VE is, therefore, suggested.

References

1. Azuma, R. and Bishop, G. (1995) Frequency-domain analysis of head-motion prediction, Proceedings of the ACM SIGGRAPH Conference on Computer Graphics 1995. ACM, New York, NY, USA.. pp. 401-408.

2. Banks, D.C. (1997) Imageswitcher: a design for reducing VR lag via parallel image generation, Computers & Graphics. v 21 n 2 Mar-Apr 1997. pp. 171-177.

3. Beuter, A., Milton, J., Labrie, C., and Glass, L. (1995) Complex motor dynamics and control in multi-looped negative feedback systems. Proceedings of the IEEE International Conference on Systems, Man and Cybernetics. Publ by IEEE, IEEE Service Center, Piscataway, NJ, USA. v 3. Available from IEEE Service Cent (cat n 89CH2809-2), Piscataway, NJ, USA. P 899-902.

4. Boff K.R. and Lincoln J.E. (1988). Engineering Data Compendium: Human Perception and Performance. TA166.E54 1988, 620.8'2 87-19560. Human Engineering Division, Harry G. Armstrong Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, OH 45433, USA.

5. Bryson, S. (1993) Effects of lag and frame rate on various tracking tasks. Proceedings of Spie - the International Society for Optical Engineering, vol.1915, 1993, pp.155-66. USA.

6. Bryson, S. and Fisher, S.S. (1990) Defining, modeling, and measuring system lag in virtual environments. SPIE vol. 1256. Conference on stereoscopic display and applications, Santa Clara, 1990.

7. Bullinger, H.J. and Fischer, D. (1998) New concepts for the development of innovative products – digital prototyping. Plenary paper. Proceedings

of the third annual Inrenational Conference on Industrial Engineering Theories, Applications and Practice. 28-31, December, Hong Kong.

8. Chung, G.K.M., So, R.H.Y., and Lee, N. K. S. (1998) A PC-based Virtual Reality System for Facility Layout Design. Proceedings of the first world congress on ergonomics for global quality and productivity. 8-11, July, Hong Kong. p. 205-208.

9. Cooper, G. E. and Harper, R. P. Jr. (1969) The use of pilot ratings in the evaluation of aircraft handling qualities. NASA TN-D-5153.

10. Conklin, J.E. (1957) Effect of control lag on performance in a tracking task. J. Exp. Psychol., 53:261-268.

11. Conklin, J.E. (1959) Linearity of the tracking performance function. Percept. Mot. Skills, 9:387-391.

12. Dizio P. and Lackner, J.R. (1997) Circumventing side effects of immersive virtual environments. Design of Computing Systems: Cognitive Considerations. Proceedings of the International '97). Elsevier. Amesterdam, Netherlands, v.2, 1997, pp. 893-6.

13. Ellis, S.R., Bréant, F., Menges, B.M., Jacoby, R.H. and Adelstein, B.D. (1997a) Operator interaction with virtual objects: effect of system latency. Proc. of the 7th International Conference on Human-Computer Interaction, 24-29 August, San Francisco, CA, pp 973–976.

14. Ellis, S.R., Dorighi, N.S., Menges, B.M., Adelstein, B.D. and Jacoby, R.H. (1997b) In search of equivalence classes in subjective scales of reality. Proceedings of HCI International '97, Elsevier, Amsterdam pp. 873-876.

15. Ferell W.R. (1965). Remote Manipulation with transmission delay. IEEE Transactions on Human Factors in Electronics. HFE-6, 24-32.

16. Fitts P.M. and Posner M.I. (1967), Human performance. Belmont, Calif.: Brooks/Cole.

17. Fitts, P.M. and Peterson, J.R. (1964). Information capacity of discrete motor responses. Journal of Experimental Psychology, 67, 103-112.

18. Glass, L., Beuter, A., and Larocque, D. (1988) Time delays, oscillatoins and chaos in physiological control systems, Mathematical Bioscience, vol. 90, pp. 111-125.

19. Guedon, O., Vercher, J. L., and Guthier, G. M. (1995). Human Operator Adaptation to a new visuo-manual relationship. IFAC Man-Machine Systems, Cambridge, Massachusetts, USA, 1995, pp. 437-442

20. Hash, P.A.K. and Stanney, K.M. (1995) Control: A Primary Driver of Cybersickness. Advances in Industrial Ergonomics and Safety VII, Edited by A.C. Bittner and P.C. Champney. Taylor & Francis, London, pp. 225-229.

21. Hoffmann E.R. (1992). Fitts' law with transmission delay. Ergonomics, 35, 37-48.

22. Homola, A., Chaloupka, J., Antos, K. and Jezek B. (1997) Hygiene aspects of the VR systems applications. Information Technology Applications in Biomedicine. ITAB '97. Proceedings of the IEEE Engineering in Medicine and Biology Society Region 8 International conference (Cat.No.97TH8342). IEEE. 1997, pp. 56. New York, NY, USA.

23. Jagacinski, R.J. and Monk, D.L. (1985). Fitts' law in two dimensions with hand and head movements. Journal of Motor Behavior, 17, 77-95.

24. Kawara, T., Ohmi, M. and Yoshizawa, T. (1996) Effects on visual functions during tasks of object handling invirtual environment with a head mounted display, Ergonomics. v 39 n 11 Nov 1996. pp. 1370-1380.

25. Kenyon, R.V. and Afenya, M.B. (1995) Training in virtual and real environments. Annals of Biomedical Engineering. Vol.23, pp. 445-455.

26. Keran, C.M., Smith, T.J., Koehler, E.J. and Mathison, P.K. (1994) Behavioral Control Characteristics of Performance under Feedback Delay. Proceedings of the Human Factors and Ergonomics Society 38th Annual Meeting, v.2, pp.1140-4.

27. Kozak J.J., Hancock, P.A., Arthus, E.J. and Chrysler, S.T. (1993) Transfer of training from virtual reality. Ergonomics, Vol.36, No.7, pp.777-784.

28. Kyger, D. and Maybeck, P.S. (1998) Reducing lag in virtual displays using multiple model adaptive estimation, IEEE Transactions on Aerospace & Electronic Systems. v 34 n 4 Oct 1998. pp. 1237-1248.

29. Kyger, D. W. and Maybeck, P. S. (1997) Reducing lag in virtual displays using multiple model adaptive estimation, Proceedings of the American Control Conference. v 4 1997. IEEE, Piscataway, NJ, USA,97CH36041. pp. 2536-2541.

30. Levine, O.H. and Mourant, R.R. (1996) Effect of visual display parameters on driving performance in a virtual environments driving simulator, Proceedings of the Human Factors and Ergonomics Society. v 2 1996. Human Factors and Ergonomics Society, Inc., Santa Monica, CA, USA. pp. 1136-1140.

31. Lin, F., Hon, C.L. and Su, C.J. (1996) A virtual reality based training system for CNC milling machine operations. Annual journal of IIE(HK), pp.13-16.

32. MacKenzie, I.S. and Ware, C. (1993) Lag as a determinant of human performance in interactive systems. Proceedings of InterCHI'93, ACM 0-89791-575-5/93/0004/0488. pp. 488-493.

33. Miall, R.C., Haggard, P.N. and Cole, J.D. (1995) Evident of a limited visuo-motor memory used in programming wrist movements. Exp. Brain Res., 107:267-280.

34. Miall, R.C., Weir, D.J. and Stein, J.F. (1985) Visuomotor tracking with delayed visual feedback. Neuroscience v.16, n.3, pp.511-520.

35. Olano, M., Cohen, J., Mine, M. and Bishop, G. (1995) Proceedings of the Symposium on Interactive 3D Graphics 1995. ACM, New York, NY, USA.. pp. 19-24.

36. Richard, P., Birebent, G., Coiffet, P., Burdea, G., Gomez, D. and Langrana, N. (1996) Effect of Frame Rate and Force Feedback on Virtual Object Manipulation, Presence, v.5, Issue 1, 1996, pp. 95-108.

37. Schaufler, G. and Sturzlinger, W. (1996) Three dimensional image cache for virtual reality, Computer Graphics Forum. v 15 n 3 Sep 1996. pp. 227-235.

38. Sheridan T.B. and Ferrell W.R. (1963). Remote manipulative control with transmission delay. IEEE Transactions on Human Factors in Electronics, HFE-4, 25-29.

39. Smith, K.U. (1962) Delayed Sensory Feedback and Behavior. Philadelphia, PA: W.B. Saunders.

40. So, R.H.Y. and Chung, G.K.M. and Goonetilleke, R.S. (1999) Target-directed head movements in an immersive virtual environment: predicting the effects of lags using Fitts' law. Human Factors, in press.

41. So, R.H.Y. and Griffin, M.J. (1992) Compensating lags in head-coupled displays using head position prediction and image deflection. J. Aircraft. 29(6): 1064-1068.

42. So, R.H.Y. and Griffin, M.J. (1993). Effect of lags on human performance with head-coupled simulators. (Tech. Report AL/CF-TR-1990-0101). Human Engineering Division, Armstrong Laboratory, Wright-Patterson AFB, Ohio. National Technical Information Service, 5285 Port Royal Road, Springfield, Virginia 22161, U.S.A.

43. So, R.H.Y. and Griffin, M.J. (1995a) Head-coupled virtual environment with display lag. Chapter 5 in: Simulated and virtual realities. Editor: K.Carr and R.England. Published: Taylor and Francis, London. ISBN 0-7484-0129-6.

44. So, R.H.Y. and Griffin, M.J. (1995b) Effects of lags on human operator transfer functions with head-coupled systems. Aviation, Space and Environmental Medicine, Vol.66, No.6, June 1995, pp. 550-556.

45. So, R.H.Y. and Griffin, M.J. (1995c) Tracking performance with a head-slaved pointing instrument with lags. In: Contemporary Ergonomics, Proceedings of the Annual Conference of the Ergonomics Society, University of Kent, Canterbury, 4-6 April. Editor: S.A.Robertson, Published: Taylor and Francis, London, pp. 74-79. ISBN 0-7484-0328-0.

46. So, R.H.Y. and Griffin, M.J. (1995d). Modelling the effects of display lags and reticle lags on head tracking performance. ISVR Contract Report No.95/25. August. Institute of Sound and Vibration Research, University of Southampton, England.

47. So, R.H.Y. and Griffin, M.J. (1996) Experimental studies of the use of phase lead filters to compensate lags in head-coupled visual displays.

IEEE Transactions on Systems, Person, and Cybernetics. Vol. 26, No. 7, July 1996.

48. So, R.H.Y., Chung, G.K.M. and Goonetilleke, R.S. (1999) Target-directed head movements in an immersive virtual environment: predicting the effects of lags using Fitts' law. Human Factors, in press.

49. Strauss, S. (1995) Cybersickness: the side effects of virtual reality. Technology Review. v. 98, July 1995, pp. 14-16.

50. Taylor, V. E., Chen, J. and Huang, M. (1996) Identifying and reducing critical lag in finite element simulations. IEEE Computer Graphics & Applications. v. 16, July 1996, pp. 67-71.

51. Ware, C. and Balakrishnan, R. (1994a) Reaching for Objects in VR Displays: Lag and Frame Rate, ACM Transactions on Computer-Human Interaction, 1994, v.1, Issue 4, pp. 331-356.

52. Ware, C. and Balakrishnan, R. (1994b) Target acquisition in fish tank VR: The effects of lag and frame rate, Graphics Interface 1994. Canadian Information Processing Soc, Toronto, Ont, Can.. pp. 1-7.

53. Watson, B., Spaulding, V., Walker, N. and Ribarsky, W. (1997) Evaluation of the effects of frame time variation on VR task performance, Proceedings - Virtual Reality Annual, International Symposium 1997. IEEE, Los Alamitos, CA, USA,97CB36033.. pp. 38-44.

54. Woltkamp, J. and Ramhandran, S. (1988) Determination of helicopter simulator time delay and its effects on air vehicle development (AIAA 88-4620-CP). Paper presented at the AIAA Flight Simulation Technologies Conference, Atlanta, September 1988.

APPENDIX A: Experimental instructions

Effect of Lag experimental instruction (Continuous Task)

Aim:

1. Investigate the effects of hand and head-related lags on a manual continuous tracking task.

Task: Use the tip of index finger to track on a moving target as accurately as possible.

Note:

1. **When your virtual finger is touching the target, the target will change to light blue color, try your best to keep the target in LIGHT BLUE color. The aim is to touch the target as accurately as possible.**
2. **When the task start, you should trace the target as accurately as possible. The aim is to minimize the tracking error.**

Procedure

1. Please sit on a chair and adjust the height of the chair, so that you can sit comfortably.

2. After the start up, the system will go through an initialization process. It is **important** to keep you hand and head still until experimenter told you to start.

3. At the beginning, you will see a "About to Start!" sign. (Fig.1) At this time, if you think yourself is ready to start the experiment, please tell the experimenter, then he will start the experiment.

4. At start you could see a "Ready?" sign, and a virtual hand. Please touch the target with your virtual index finger's tip (Fig. 2).

5. Keep your finger at the same position, until the "Ready?" is disappeared. At that time, the target will start to move, and you have to track the moving target with the tip of the virtual index finger **as accurately as possible**.

6. The duration of the tracking task is 1.5 minutes, after 1.5 minutes the task is finished.

7. After each task, you will be asked to complete a form, which will be presented on the HMD. (see attachment)

NOTE: 1. Total 10 tasks: with different time lags, each lag will be repeated twice. Do you have any question? If no, please read and sign the subject consent form.

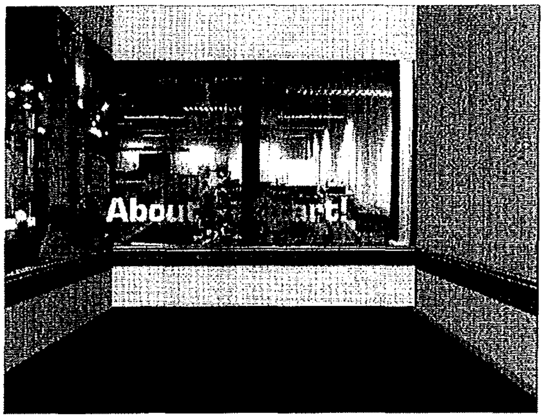

Fig. 1: About to Start!

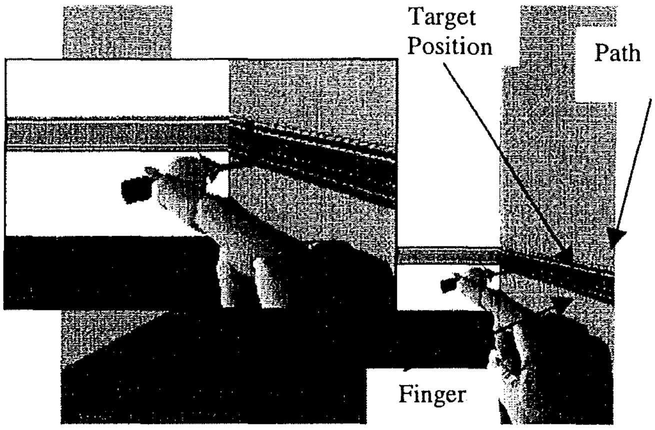

Fig. 2: Tracking the target!

Effect of Lag experimental instruction (Discrete Task)

Aim:

1. Investigate the effects of hand-related lags on a discrete manual control task.

Task: Hit a target square using the tip of the virtual index finger as Fast as possible. When the square is hit the color will be changed.

Note:

When the task start, you should hit the square as fast as possible a successful hit is indicated by a change in color. The aim is to have the shortest hitting time.

Procedure

1. Please sit on a chair and adjust the height of the chair, so that you can sit comfortably.
2. **Please keep your back contact with the sit back through out the experiment.**
3. 9 practices for you to optimize to the appropriate speed which may be a function of lag. The aim is to familiar with the system and also the lag.
4. At the beginning, you will see a "About to Start!" sign, virtual hand, and a blue square on the left surrounding with a red boarder (Fig.1). Place the tip (Yellow Color) of the virtual index finger at the square on the left (Blue Color). Then the square will be changed to green color. At this time, if you think yourself is ready to start the experiment, please tell the experimenter, then he will start the experiment.
5. After the experimenter pressed a key the "Ready?" will disappear, the boarder will change to yellow color, and a target (Red Color squares) will appear. (see Fig 1)
6. **(DON'T MOVE YET!)**. Keep your hand at the same position, until the yellow border is appeared. At that time, you have to move hit the Right Target Square (Red Color) **as soon as possible** (Fig. 2).
7. After you have hit the target, it will change the color to green and then you have to hit the left square. You must come back to the left square, and restart the next task. Go to step 4.

NOTE: **1. Total 5 sets of 48 runs: with different time lags, distances**
2. After each set, you will have about 1 minute for resting.

Do you have any question? If no, please read and sign the subject consent form.

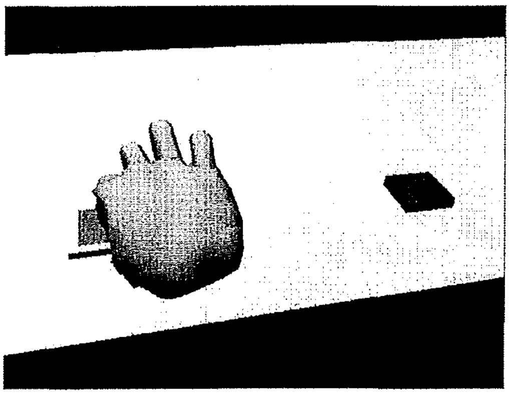

Fig. 1: On Source Position

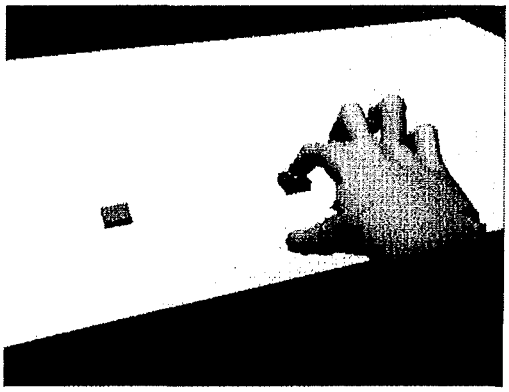

Fig. 2: On Destination Position

APPENDIX B: Sample of Subject Consent Form

STATEMENT OF CONSENT TO TAKE PART
AS A SUBJECT IN THE Effect of Lag Experiment

Name: ____________________
Age: __________

Inter-Ocular distance: ____________
Offset-Y: ________
Offset-Z: ________
Forearm size: _______

DECLARATION

I consent to take part in an experiment. And I understand that I may at any time withdraw from the experiment and that I am under no obligation to give reasons for withdrawal or to attend again for experimentation.

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

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

Signature of Subject ____________________ Date ______________________

Signature of Experimenter ________________ Date ________________________

Subject consent form – Effect of Lag / March 1999