Bimanual and Dual-Cursor Control for Constrained Navigation and Selection

A thesis presented
by

Xu Xia

to
The Department of Computer Science
in partial fulfillment of the requirements
for the degree of
Master of Science
in the subject of

Computer Science

The University of Manitoba
Winnipeg, Manitoba

THE UNIVERSITY OF MANITOBA

FACULTY OF GRADUATE STUDIES

*****

COPYRIGHT PERMISSION

Bimanual and Dual-Cursor Control for

Constrained Navigation and Selection

BY

Xu Xia

A Thesis/Practicum submitted to the Faculty of Graduate Studies of The University of

Manitoba in partial fulfillment of the requirement of the degree

Master of Science

Abstract

Constrained navigation and selection are two very common tasks performed in a variety of environments, such as in medical tele-operation units, games, and map browsers. In this thesis we explore the benefits of Guiard's theory of bimanual control for the tasks of constrained navigation and selection. Guiard's theory suggests that under certain conditions bimanual operation can be more effective than unimanual control. In this thesis I initially seek out whether Guiard's theory applies to an environment with constrained navigation and selection requirements. The results of the first two experiments suggest that unimanual operation is more effective than bimanual control in constrained navigation environments. However, a comparison between different bimanual methods suggests that Guiard's theory is still valid and one can delegate the task of constrained navigation to the non-dominant hand and selection to the dominant hand. The results of the first two experiments led to the design of a novel navigation technique with unimanual control, referred to as the dual-cursor navigation technique. The dual-cursor navigation method borrows principles from Guiard's theory of bimanual control and applies these to the concept of a constrained navigation and selection. The results of our study show that the dual-cursor navigation mechanism is more effective than the typical unimanual navigation in constrained environments. The contributions can assist interaction designers in developing adequate tools for bimanual operation.

Acknowledgement

I am grateful to my advisor Dr. Pourang Irani for his insightful guidance, friendship and motivation during my research. Dr. Irani introduced me to an attractive research area in HCI. I am grateful for Dr. Irani's time and his patience in revising my work. I regard myself as being extremely grateful and thankful to Dr. Irani, because he has been more than just an advisor.

I am greatly indebted to my parents. They guide me and encourage me in all aspects of my life and studies. Especially, I am greatly thankful to my fiancée Jing Wang for her idea, assistance and contribution to my research. She is very talented in computer science and contributed many critical ideas to this project.

I am thankful to all participants in my experiments and all my friends for their help with my reseach.

Table of Contents

Table of Figures

List of Tables

List of Charts

Publications

Xia, Xu, Irani, Pourang and Jing Wang. "Evaluation of Guiard's Theory of Bimanual Control for Navigation and Selection", HCI International 2007

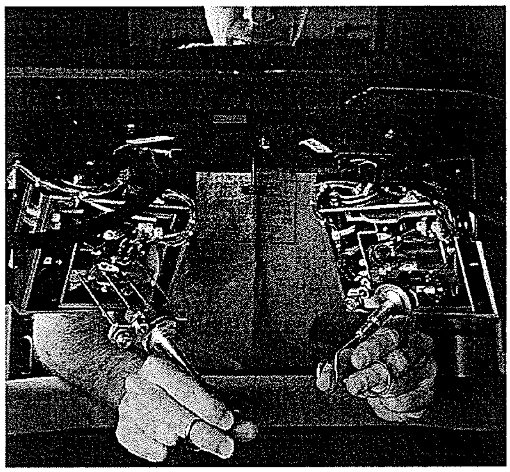
Chapter 1 – Introduction

Humans use both hands frequently to perform everyday actions. We naturally use our hands to perform tasks such as picking up an item, washing dishes or in more precise tasks such as hammering a nail to the wall. Typically, our manual operations can be divided into two types: unimanual (one-handed) and bimanual (two-handed). The bimanual operations can be further categorized into symmetric, where both hands perform similar tasks and have the same level of importance; and asymmetric, in which the two hands have different roles at the same time. In bimanual situations, people tend to use one hand for fine operations while the other hand provides a rough guide for the first hand [14]. Researchers have termed these two hands as Dominant Hand (DH) and Non-Dominant Hand (NDH). To a right-handed person, the DH refers to their right hand, and the NDH refers to their left hand.

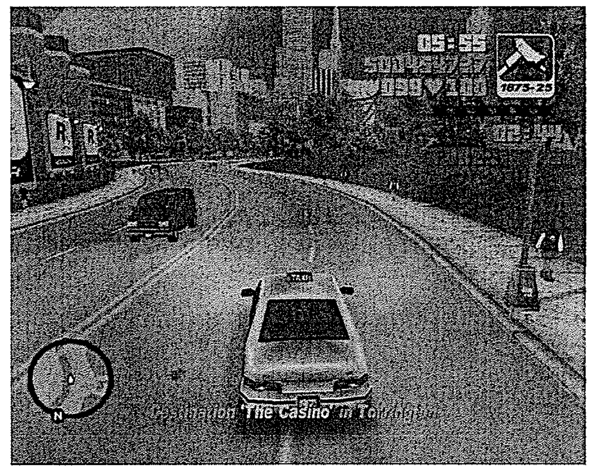
As a natural way of functioning, two-handed interactions take place in everyday tasks, and with minimal training. In addition, using two hands can reduce the task switching time as is commonly the case in one-handed operations. Generally, bimanual interaction, with regards to computing related navigation and selection, is designed to have two input devices and two corresponding cursors. However, people are limited to using their dominant hand to operate the computer in current interfaces. Studies regarding bimanual interactions have relied on knowledge in the area of cognitive motor behaviour or bimanual control. In this thesis, I investigate the effectiveness of applying theories of bimanual control to tasks that involve navigation in a constrained virtual environment and selection of objects. Several real world applications benefit from understanding the role both hands play in navigation and selection. For example, in tele-medicine surgeons in practice interact with virtual models where one hand is used for moving around the environment (navigation) and the other for doing more precise tasks (such as stitching or selecting). The goal of this thesis is to test whether theories of bimanual interaction can be applied to tasks that involve constrained navigation and selection.

1.1 What is Constrained Navigation?

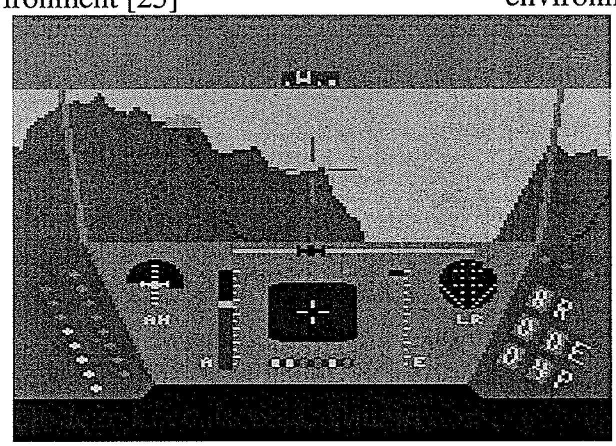
Constrained navigation is defined by a set of restraints on the user's navigation path. This is typical in environments in which careful movements are needed to arrive to the target destination. For example in telesurgical applications, the physician needs to control their movements along well defined constraints. Careful navigation is necessary to avoid certain objects. Selection is also very precise for pointing at objects. In addition to telesurgical applications, simulated flight control systems and gaming environments also operate under constrained navigation and selection of items. Constrained navigation differs from typical navigation in that the user does not have complete freedom over their movement path. In this thesis I restrict my investigation of bimanual control to constrained navigation and selection. Whereas many constrained navigation environments occur in 3D, I also restrict my study to 2D constrained movements, typical of map systems, 2D games as well as 2D control systems. My results can be eventually transferred to 3D environments.



(a) Constrained navigation in a telesurgery environment [25]



(b) Constrained navigation in a gaming environment



(c) Flight control system with constrained navigation

Figure 1.1: Different constrained navigation systems.
The user's path is restricted in terms of where they can move next.

The organization of this thesis is as follows: in chapter 2, I cite the relevant background to the research; in chapter 3, I provide a description of the first solution to the problem of constrained navigation and selection, based on bimanual control; following this, I describe the experimental design and results in chapter 4; in chapter 5, I introduce a novel dual-cursor technique and describe the results of the evaluation. I finally conclude in chapter 6 with a discussion of my results and directives for future work.

Chapter 2 – Related Work

Many studies have examined the nature of bimanual operation and have compared the efficiency between unimanual and bimanual operations, and between symmetric and asymmetric bimanual interactions. Based on a number of theories, researchers have also introduced new bimanual interaction techniques. I present a survey of the literature pertinent to bimanual interaction and the literature that is related to the research here. In the following section, I describe the major results that relate to my study.

2.1 Bimanual versus Unimanual Operation

A number of experiments have been carried out to compare input efficiency between two-handed and one-handed interactions. Similarly, with bimanual interaction, several results describe the nature of symmetric and asymmetric tasks. In one classic study, Buxton and Myers [6] compared the distribution and efficiency of labour with unimanual to bimanual interactions. The participants in their study were grouped into experts and novices. In the first experiment, all the subjects were provided with a graphical drawing interface. Their task consisted of positioning a square in a target place, and to scale it to an expected size. The participants did the experiment with one hand and with two hands. The results of this experiment showed that subjects perform better when they use both hands for simultaneously positioning and scaling an object. In the second experiment, the subjects were required to scroll a word processing document until they found a target word. Buxton and Myers found that, both experts and novices improved in efficiency after changing from one hand to two hands. Furthermore, their results show that the improvement is better for novices than experts. The conclusion of their study suggests that two-handed interaction, for their specific tasks, were more efficient than one-handed operation.

Kabbash et al. [18] examined a one-handed technique and three different types of two-handed techniques. In their experiments, the subjects selected a colour from a movable menu and drew lines between displayed vertices. The three bimanual techniques were: i) each hand controls a different cursor with same functionality; ii) the left hand is only responsible for moving the menu, while the right hand is responsible for all the other functions; iii) uses a technique called Toolglass [5], where the colour selection menu is transparent, so that the users can see through the menu. They captured the amount of visual diversion, motor operation and the time for completing the tasks. Their results show that, Toolglass has the least number of motor operations. In addition, only the Toolglass technique out-performs the unimanual technique, while the other two techniques take more time than the unimanual operation. Kabbash et al. concluded that, the method in which the bimanual technique is designed is critical to its efficiency, and "if designed improperly, two hands can be worse than one" [18].

Leganchuk et al. [21] compared two bimanual techniques with the traditional unimanual approach. In their research, two experiments were carried out. In the first experiment, the subjects were required to position and resize either an ellipse or a rectangle to minimally cover a given figure in one of six predefined shapes. This experiment compared the traditional unimanual technique (U), a symmetric bimanual technique (SB), and a bimanual Toolglass technique (BT). Their results show that, the bimanual techniques outperform the unimanual technique by 17%, while there was no significant difference between the two bimanual techniques. In the second experiment, the users were able to practice before starting the experiment. This time, only U and BT were compared. Their results show that BT outperformed U by 39%. Leganchuk et al. concluded that, cognitive ability is important for performance results, and the mental representation of an ongoing action is important for bimanual interaction performance [21].

In a follow-up to Leganchuk et al. [21], Owen et al. [24] proposed that because the two hands would provide more feedback, manipulation capability, and help to evaluate the data, using both hands are more expressive than using one hand. They investigated the time of completing a unimanual operation and that of completing two bimanual operations with an integrated device for both hands or two separated input devices for each hand. The task in their experiments consisted of manipulating a curve to match a given line. The authors hypothesized that the one hand task would take longer to complete than the two-hand completion time. They conjectured that part of the overhead would result from a certain amount of cognitive effort. Their results show that the two-handed conditions were approximately 40% faster than the one-handed conditions. When the task is more complicated, both hands are more efficient. In this study, Owen et al. [24] emphasized integrating bimanual interaction in one input device. However, there is no evidence that shows that an integrated device will outperform a non-integrated set-up.

Latulipe et al. [19, 20] compared the efficiency between unimanual (UNI), symmetric bimanual (SYM) and asymmetric bimanual (ASYM) actions using a one-mouse interface for unimanual and two-mice interface for bimanual. In their experiments, the users are required to perform an image rotation and scale task. The researchers measured the completion time of performing a task; the response time after the image was shown until the mouse starts to move; the accumulative switch time of the period between the change from one mouse to the other; and the movement time which is the completion time minus the other two. Their results show that the mean completion time of SYM is 87% faster than UNI, and ASYM is 42% faster than UNI. Latulipe et al. [20] concluded that, asymmetric bimanual outperforms unimanual actions, while symmetric bimanual technique is the best among the three designs.

In another study, Hinckley et al. [16, 17] designed a task in which the subjects were asked to align virtual objects using one hand and two hands. They provided two tools to control two separate virtual objects. The object would move and rotate according to the operation allowed by the tool. Users could only pickup one tool at a time for the unimanual situation; and would pickup both tools in the bimanual condition. The degree of angle separation between the two objects and the distance between the two objects were recorded. The results show that when subjects use both hands they perform the task more accurately than using one hand only.

The studies above examined the benefits of bimanual interaction in comparison to unimanual operation. The results generally indicate that bimanual interaction, based on a given task, can outperform unimanual interaction. None of the studies, to the best of my knowledge, have investigated the distribution of labour between both hands for the tasks of constrained navigation and selection. In particular, the central question in my thesis inquires as to whether it is better to perform navigation tasks with the NDH and the task of selection with the DH, or the opposite. To resolve this question I first provide a description of Guiard's Kinematic Chain model that has motivated my investigation.

2.2 Guiard's Kinematics Chain Model

Many bimanual interactive designs have been proposed for various industrial or real-world applications [7, 12, 17, 18, 19, 20]. For example, it has been proposed to replace the traditional black photographic tape drawing technique with an asymmetric two-handed automotive design interface [2]. Chatty [8, 9] suggested that the basic logic of assigning tasks to two-handed interaction can have a significant impact on performance and can result in interactions where two hands will be faster than using one hand.

Numerous studies [7, 17, 18, 20] show that, bimanual interaction input interface can be designed into various ways. However, before we are able to split tasks into two hands, the most important concern consist of determining the role of each hand, and distinguishing the tasks that should be relegated to either hand. Furthermore, most studies show that, bimanual interaction can be designed in different ways. In particular, the designers are faced with the question of how to distribute the tasks between both hands. To determine the method in which to split the tasks between the left and right hands, it is important to first determine the role of each hand, and to distinguish the tasks that each hand is better at.

To get an answer to the question of the role of each hand, and how to distribute the various tasks between the two hands, one can base his/her work on Guiard's theory of bimanual interaction, which is also referred to as Guiard's kinematic chain model. Guiard [14, 23] developed a model to demonstrate the relationship between the roles of both hands in a bimanual application. He defines human hands as two motors as they can make movements, regardless of the internal mechanism of the motion. The movement of such a motor is described in Figure 1.1. The motor is controlled by an information processing system (IPS), which is analogous to the human brain when the motor represents a human hand. A reference position (RP) generates an input to the motor, and the output of the motor produces a variable position (VP).

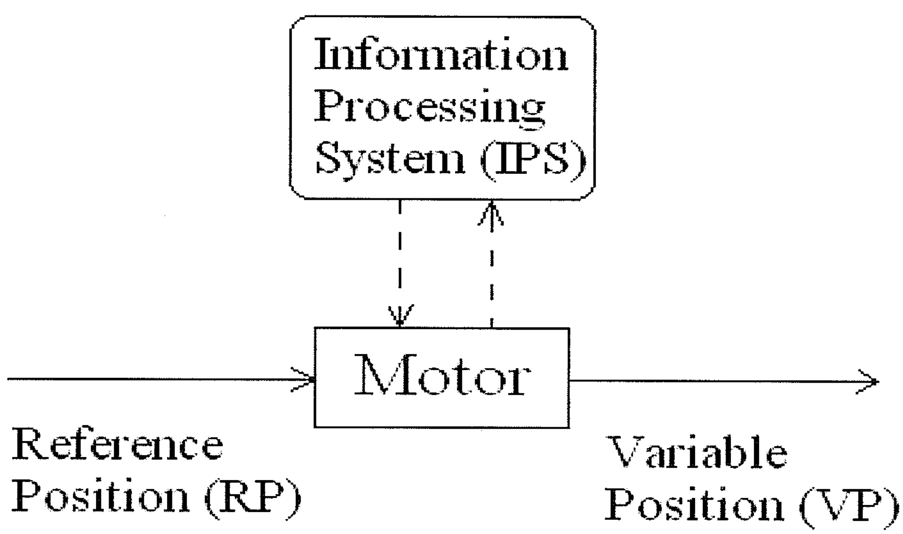


Figure 2.1: A high-level representation of a typical motor processing system. Adapted from [17].

Guiard first identified three categories of bimanual actions: orthogonal, where the tasks of each hand are not related; parallel, where the two hands perform the same task to achieve the same goal; and serial, where the output of one hand is the input of the other hand. In contrast to the first two conditions, the third type of interaction is more natural. Therefore, to take advantage of bimanual interaction, it is best that two hands perform different tasks. This generally often leads to a serial method of processing such that the output from one hand is the input of the other hand. This serialized model is called the *kinematic chain model* or *Guiard's model of bimanual control* [14]. In Guiard's model, the non-dominant hand (NDH) acts before the dominant hand (DH), and typically performs a coarse action. The NDH also provides a frame or reference to the DH. The DH then performs a finer action, which requires the most significant cognitive effort from the user. This relation is depicted in Figure 2.1. The reference position (RP) for the non-dominant hand (NDH) is the input to the NDH motor. After the movement of the NDH motor, the NDH produces a variable position (VP), which together with the RP of the dominant hand (DH) becomes the input of the DH motor. The motion of the DH will then generate a VP for the DH. This chain may contain many motors in a serial manner, and the VP for the DH can then become part of the input for the next NDH motor action. According to Guiard's model, the chain should always start from the non-dominant hand motor (NDH), and usually end at the dominant hand motor (DH).

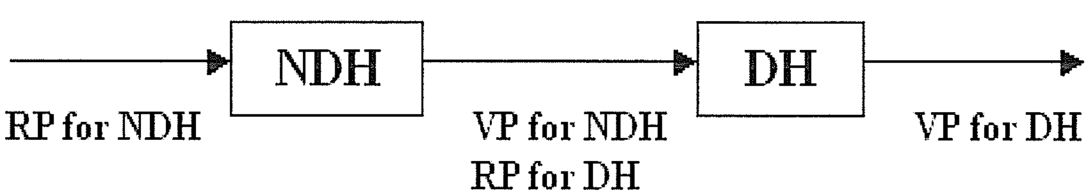


Figure 2.2: Guiard's kinematic chain model. Adapted from [17].

Guiard's model is purely descriptive and is summarized in Table 2.1. The actions in this model can be explained by means of a drawing application designed to take advantage of both hands to draw images. The painter is given a template and a pencil. The template will be used by the non-dominant hand (NDH) and the pencil is manipulated by the dominant hand (DH). For simplicity, let us assume that the painter is right-handed and so the NDH is the left hand, and the DH is the right hand. To draw figures, the painter will first take the template in the left hand. The template is moved in the drawing space until the painter has a good place to start. In this way the left-hand is leading the right hand and is also setting the spatial frame of reference for the right hand (first two characteristics of the NDH as depicted in Table 2.1). In handling the template the painter will typically perform coarse movements (third characteristic of the NDH in Table 2.1). Once the position of the template is fixed, the painter moves the DH toward the NDH (first characteristic of DH in Table 2.1) and works within the established frame of reference set by the left-hand (second characteristic of DH in Table 2.1). Finally, to get an image the painter has to perform fine movements (third characteristic of the DH in Table 2.1). This set of actions is properly encapsulated in Guiard's theory of bimanual control.

Hand	**Role and Action**
Non-Dominant (NDH)	- Leads the dominant hand - Sets the spatial frame of reference for the dominant hand - Performs coarse movements
Dominant (DH)	- Follows the non-dominant hand - Works within the established frame of reference set by the non-dominant hand - Performs fine movements

Table 2.1: The roles of both hands in Guiard's Model. Adapted from [7].

2.3 Applications of Guiard's Model

Guiard's kinematics chain model has been applied to a variety of studies in human-computer interaction (HCI). Most of the research in HCI has either adopted this model for designing a new interactive technique or to verify the validity of this model in a given application environment. I will first describe several studies that have been designed to validate Guiard's model. Then I will describe another set of studies that have used Guiard's model to guide their designs.

Balakrishnan et al. [3] focused on the "right-to-left spatial frame of reference in manual motion", which they defined as "Guiard reference principle" or "Kinesthetic reference frames". In this study, they compared conditions when the input spaces for two hands are separated and when the input spaces are united as one. Balakrishnan et al. [3] designed a set of experiments using two pucks and one tablet. Each hand controls a puck, and both pucks move on the tablet. In these experiments, the puck in the NDH is responsible for moving a Toolglass, which is a 50% transparent square split into four equal size sub-squares. Each sub-square on the Toolglass has a different colour. The puck in the DH moves a cursor, and there is a button on this puck that can be pushed. The participants were required to draw lines between a number of squares. When drawing a line, the NDH should first move the Toolglass on top of the starting square. Then the DH moves the cursor over the Toolglass, and clicks the button when the cursor is on the sub-square with the same colour as the destination square. The button should stay pushed until the cursor is moved on top of the destination square. The line drawing is done when the button is released. There are only two squares shown at the beginning, and there is only one more square shown after a line is drawn. So each time, there is only one line to draw. In addition, the adjacent squares are shown in different colours so the colour of the line keeps changing as well. This study recorded the task completion time and error rates. Their results showed that as long as proper visual feedback is provided, Guiard's model is independent of the integrity of the workspace for both hands.

Cutler et al. [10] has implemented a virtual environment to study Guiard's Kinematics Chain model. In this virtual environment, users can manipulate given virtual objects using interactive tools. The tools can be used either as one-handed or two-handed. In a two-handed condition, the left hand tool is used for positioning, and the right hand tool performs more precise tasks, such as zooming and rotating. This study assumes the left hand as NDH, and right hand as DH in the same way that Balakrishnan et al's experiments do [3]. The observation from the experiments showed that the Guiard's theory represents a good model for supporting two-handed interactive input in virtual environments.

Several studies have applied Guiard's Kinematics Chain model to their proto-typical designs. An example is a two-pointer input interface for 3D applications designed by Zeleznik et al. [26]. In this design, the tasks are distributed among both hands to perform rotations, scaling and translation of the 3D object. The task of rotation was delegated to the NDH which was responsible for determining the axis, or point along which the rotation is possible and the DH is used for performing the rotation task. For scaling, the NDH cursor holds the object, and the DH is allowed to change the size of the object. Translating can be done by positioning both cursors on the object and moving them toward the expected direction. They found that Guiard's model was highly applicable to the interaction design they developed.

Another application is the use of Guiard's model in an asymmetric two-handed automotive design interface for replacing the traditional black photographic tape drawing technique [2]. In this design, Balakrishnan et al. [2] defined the interface as two trackers held in two hands. Each tracker has a button. The movement states of each hand combined with the state of the buttons (pushed or not) determine the current input, thus, deciding the lines to be drawn onto the display surface. Some other examples include a bimanual design with one TouchPad for the NDH, and a TouchMouse for the DH, which was proposed by Hinckley et al. [15]. A transparent Toolglass design positions the Toolglass in the NDH, and uses the DH to control the cursor [5]. Balakrishnan et al. [2] report that Guiard's model is well suited to the task of two-handed automotive design.

As described above a significant number of studies have investigated the applicability or effectiveness of Guiard's theory for bimanual control. The results vary with the different interface designs, the different experimental conditions, tasks, and design. One area that has not been investigated is the use of bimanual interaction for constrained navigation and selection tasks. Constrained navigation and selection are common tasks that are carried out in a variety of applications. Constrained navigation is predominant in virtual environments, in 3D interfaces, and in applications that require visual searching and browsing. Selection is common in most graphical user interfaces. More specifically, bimanual interaction with navigation and selection has been applied to medical tele-learning (the trainee will navigate in a virtual environment using one hand and perform selections with another), in tele-surgery (the surgeon will navigate in the environment the represents the patients body and use the other hand to perform precise stitching or picking), and in video games.

As Guiard's model provides us a definition of the relationship between the two hands, I used this theory to identify how to distribute the leading tasks and finer tasks. Latulipe et al. [19] suggested to use symmetric bimanual design as it is more efficient than unimanual and asymmetric bimanual. As a matter of fact, in our everyday life, people are more likely performing actions in asymmetric bimanual ways [14, 23]. Generally, there are two general ways of bimanual input design: add an additional cursor that will have the same functionality as the first cursor; or integrate the two input devices together. "When combining movements together, one has to manipulate events that do not occur at exactly the same time."[9] Because efficiency depends on the type of task and user strategies, I designed experiments assigning the different tasks to different hands. One hand is for navigation and the other hand is for selection. Selection is the task of pointing to different objects in the environment. Selection is the primary method of interaction in windows based interface. Navigation consists of moving the users' viewport or taking the cursor from one place to another.

In this thesis I inquire as to whether Guiard's theory of bimanual control can effectively assist in the distribution of labor between two hands for the tasks of constrained navigation and selection. More specifically, I seek to find answers to whether "designers should assign the task of navigation to the DH and selection to the NDH" or "do designers do the reverse?" Additionally, if Guiard's theory of bimanual control is not effective in constrained navigation and selection tasks can we design new navigation techniques for constrained navigation and selection? The objectives of this thesis are to verify the implication of Guiard's theory of bimanual interaction for the combined task of navigation and selection and to assess the possibility of novel interaction techniques for the given composite task.

Chapter 3 – Evaluating Guiard's Theory of Bimanual Control for Constrained Navigation and Selection

To determine how to assign tasks to the non-dominant hand and to the dominant hand, one can look closer at the characteristic features of the navigation and selection tasks. Navigation and selection require continuous and asymmetric behavior. Navigation may not require very precise movements, but rather it can be coarse. Navigation also typically sets the frame of reference under which selection may operate. Selection must be operated in a precise manner, and requires attention to details. Selection also will typically work within a frame of reference that has already been created. In the context of the dual composite task, the characteristics of navigation and selection are summarized in the table 3.1.

Navigation	Selection
- Leads selection - Sets the spatial frame of reference under which selection can operate - Can be performed by coarse movements	- Follows navigation - Is performed within the established frame of reference once the user has navigated toward his/her target - Requires fine and precise movements

Table 3.1: Characteristics of the Navigation and Selection tasks.

Given this simplistic model of navigation and selection and based on Guiard's descriptive model summarized in Table 2.1, in chapter 2, the designer can clearly assign the task of navigation to the non-dominant hand and selection to the dominant hand. Following Guiard's theory and evidence from prior work may suggest that users will perform better when navigation is relegated to the non-dominant hand and selection to the dominant hand; this constitutes the primary hypothesis. In the following sections I describe the experimental set-up I used to test the aforementioned hypothesis.

3.1 Study Methods

To verify the hypothesis I conducted two separate experiments. In the first experiment, the users performed a constrained navigation task and selection of objects in an environment where the targets are static. The second experiment is similar to the first with the additional difference that the targets are dynamic, thus, randomly moving along a path. Dynamic targets constitute the primary trait in constrained navigation environments such as games. In both experiments, I evaluate the effect of delegating the tasks of navigation and selection to the dominant and non-dominant hands as proposed by Guiard's model. To match the given task I facilitate navigation by means of two joysticks, a distinctive input device used for navigating in constrained environments.

3.1.1 Experiment 1: Static objects

The objective of this experiment is to validate Guiard's theory for the tasks of selection and navigation with static targets.

3.1.1.a) Materials

The experiment was carried out on an Intel Pentium-IV CPU and a 20" 1280x1024 resolution display monitor. The operating system is Windows XP. The input devices for navigation and selection are two Logitech Attack 3™ joysticks.

3.1.1.b) Implementation

The implementation was completed using the Microsoft C#.NET environment. The experiment uses an MS Access™ database to record the data collected from each trial. The software implementation relies on a depth-first algorithm for generating the maze, since I use a maze within which the users perform constrained navigation and selection. I designed the maze platform using a depth-first algorithm to generate the boundaries or walls. The depth-first algorithm is a popular algorithm adopted to generate a maze, for instance in games such as EaterGame II [13]. This maze contains $n \times n$ cells, thus, n columns and n rows. All the cells have four sides that are initially constructed with walls. This algorithm starts with a pointer pointing to the first cell $C[0,0]$. It randomly picks an adjacent un-visited cell, i.e. with all four walls intact, and breakdowns the wall between them. Then the pointer moves to this new cell, and finds the next un-visited adjacent cell. If the current cell has no un-visited cells adjacent to it, the pointer returns to the previous cell before entering the current cell, and continues the search from that cell onward. The program will stop when all the cells have been visited. The modified maze is shown as in figure 3.1 with five objects distributed in the maze path and 2 cursors starting from the left bottom corner of the maze.

3.1.1.c) Task Description

To validate Guiard's theory of bimanual control, I designed a task that necessitated constrained navigation and selection. To simulate the effects of constrained navigation the user was required to travel along a maze. While moving along the maze the user is then asked to select specific objects. Navigation and selection are performed using the two joysticks. This task is performed under different conditions as described below.

The following figure depicts one of the many scenarios presented to the users in the study.

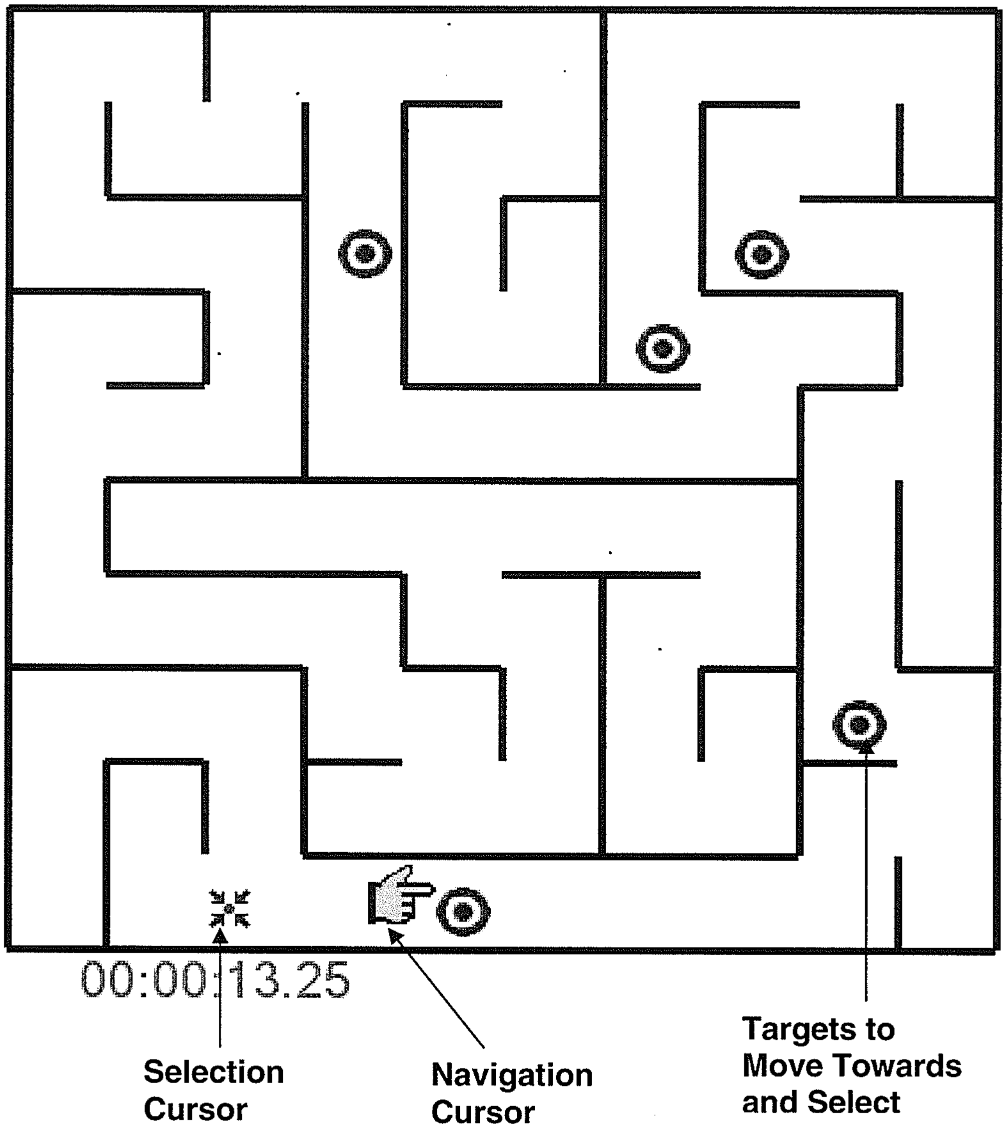


Figure 3.1: Interface used in the experiment.
A maze in 2D simulates the effects of a constrained environment.

At the start of each trial, the cursors of both joysticks are positioned at the start location, which is at the bottom left location of the maze. The user was instructed to exit the maze by navigating throughout the constraints and removing obstructions by selecting them. With the navigation joystick the users starts to navigate along the route. As the participant approaches an obstacle, he/she is required to eliminate every object that appears on the route. This task is representative of tasks that require some form of navigation toward the objects and then some selection. The navigation cursor is the only cursor that is constrained to route of the maze. The selection cursor can move freely without any obstruction on the maze map. According to this design, the user merely needs to drag the selection cursor by following the navigation cursor. This would off-load cognitive resources for the user by not concentrating on the selection task but primarily focusing on the navigation task. Figure 3.2 depicts the experimental setup with both joysticks

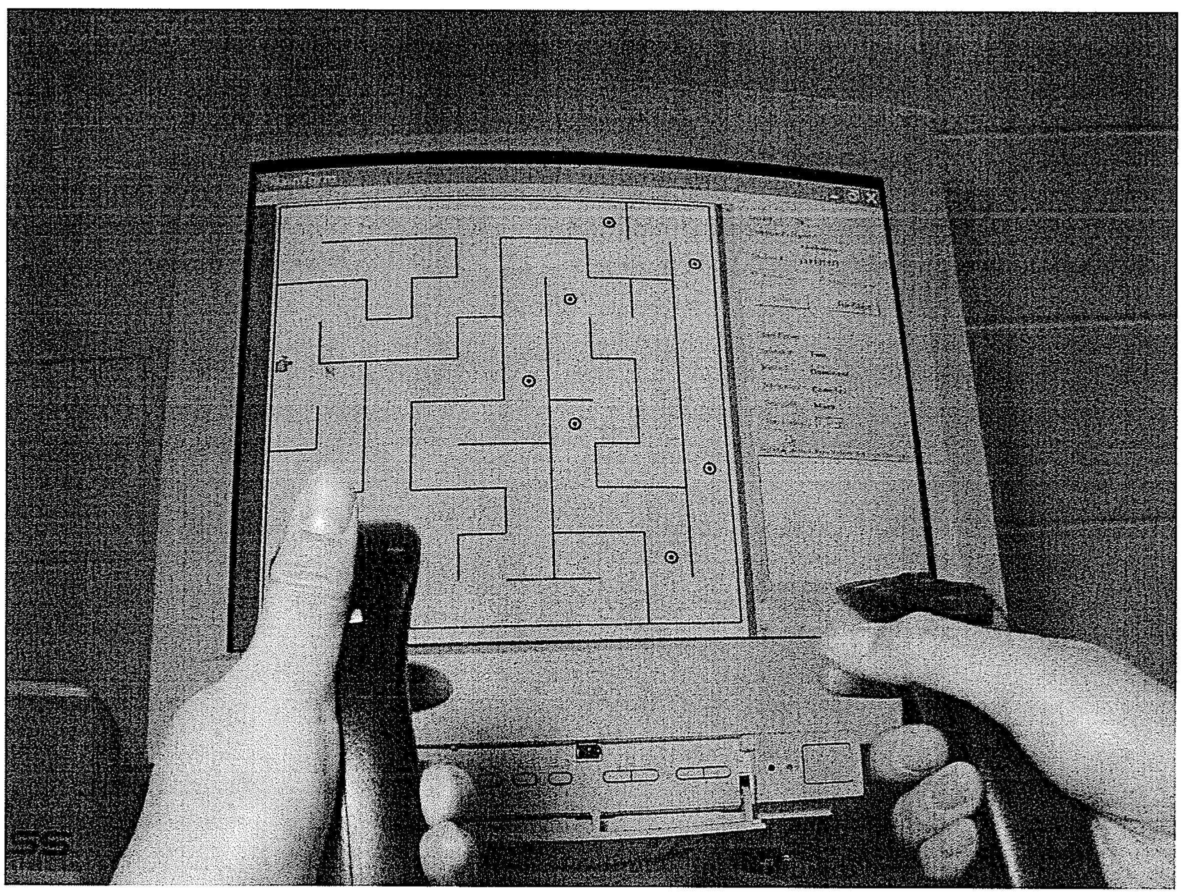


Figure 3.2: Experimental setup in experiments 1 and 2 where the user has two joysticks, one for the task of navigation and the other for selection.

3.1.1.d) Design

The experiments used a 3×2×2 within-subject design. The main factors for this experiment are:

- Task Distribution, 3 levels: unimanual operation, navigation by DH, navigation by NDH
- Width of paths, 2 levels: small (complex), large (simple)
- Number of objects, 2 levels: few, many

Each of these factors is described in detail below.

(i) Task Distribution

To verify the application of Guiard's theory for bimanual operation, the experiment distributes the tasks in three specific conditions. In the first condition (baseline condition) the user performs the task in a unimanual setting. In the second condition the navigation joystick is set to the DH (navigation by DH) and the selection joystick to the NDH. In the third condition the navigation joystick is set to the NDH (navigation by NDH) and selection to the DH.

(ii) Width of paths

To add additional complexity, the experiment varies the different widths of paths from the start to the end. This is set according to the Steering Law [1]. Accot and Zhai [1] introduced the Steering Law, which suggests that navigation performance is inversely related to the width of the path as given by the following equation: $T_C = a + b \times \int_C \frac{ds}{W(s)}$.

The a and b are constants that are empirically obtained; c is the length of the path; $\frac{1}{b}$ demonstrates the index of performance in steering; s represents the curvilinear abscissa, and $W(s)$ denotes the path width at abscissa s. This factor has two levels, one of 5 pixels and the other of 10 pixels wide.

(iii) Number of objects

To better judge differences in conditions I also introduced varying number of objects as an independent variable.

3.1.1.e) Subjects

Eleven participants were randomly chosen to conduct this experiment and were assigned to perform all the trials. Subjects were volunteers with background in economics, computer science, engineering, business, arts and high school students. The following tables show related statistical information for the subjects.

Age	15-20	20-30	30-40	40
Number	2	5	3	1

Table 3.2: Statistics of Age

Gender	Male	Female
Number	9	2

Table 3.3: Statistics of Gender

Background	Computer Science	Engineering	Economics	Arts	Business	High School
Number	3	2	2	2	1	1

Table 3.4: Statistics of Background

Experience History	Yes	No
Use of Computer (Number)	11	0
Playing Game (Number)	11	0
Use of Joystick (Number)	6	5

Table 3.5: Statistics of Experience History

3.1.1.f) Procedure

For each trial the system recorded the time it took the user to navigate and select objects in the entire maze. For each condition the user performed 10 trials. I collected the completion time for each trial. The analysis is performed on the average task completion times for each user.

3.1.2 Experiment 2: Dynamic Targets

Experiment 2 is identical to Experiment 1 with the difference that objects are moving randomly along the path. This implies that users have to navigate toward the dynamic objects to select them. The only difference between the static target experiment (experiment 1) and the dynamic target experiment (experiment 2) is that all objects are moving along a constrained path. In this experiment, the user has to track the moving targets and select them to complete the trials successfully.

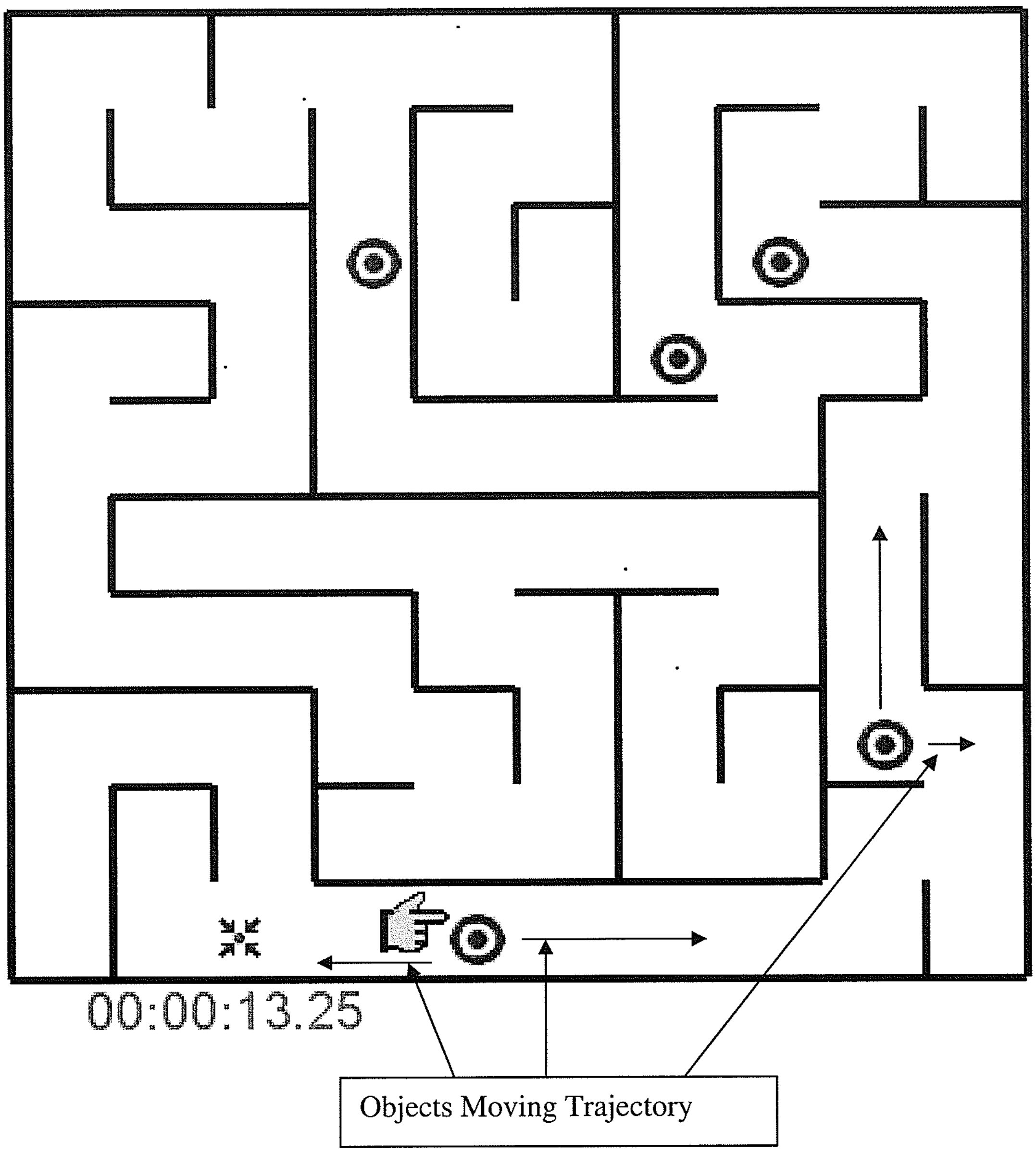


Figure 3.3: Interface used in the second experiment. Objects are moving along the maze.

3.1.2.a) Subjects

I randomly chose eight participants for this experiment. Subjects were volunteers from economics, computer science, engineering, business and arts departments. The following table shows related statistical information for the subjects. None of these participants performed experiment 1.

Age	15-20	20-30	30-40	40
Number	1	4	3	0

Table 3.6: Statistics of Participants Age

Gender	Male	Female
Number	7	1

Table 3.7: Statistics of Participants Gender

Background	Computer Science	Engineering	Economics	Arts	Business	High School
Number	1	2	2	2	1	0

Table 3.8: Statistics of Participants Background

Experience History	Yes	No
Use of Computer (Number)	8	0
Playing Game (Number)	8	0
Use of Joystick (Number)	4	4

Table 3.9: Statistics of Participants Experience History

3.2 Study Results

For each trial the system recorded the time it took the user to navigate and select objects in the entire maze. All our results (for experiments 1, 2 and 3) are analyzed using a t-test. A t-test is a statistical test, used for evaluating whether the means of two groups are statistically different. When we run a t-test, we normally obtain a p-value or probability value. We say that the difference between means is significantly different if the p-value is less than 0.05 ($p < 0.05$). The p-value indicates the probability of making a Type-II Error. A Type-II Error is when we say that a hypothesis is true when the hypothesis is in reality not true! Therefore we always want to have a smaller p-value so that we are not making an error in saying whether our claim is true when it is not.

3.2.1 Results of the first experiment

The results of the first experiment are summarized in Table 3.10 below. In Table 3.10 and in the entire analysis, a distribution method of "Dominant" infers that navigating was relegated to the dominant hand and selection to the non-dominant hand. Conversely, "Non-Dominant" means navigating with the non-dominant hand, and selecting with the dominant hand.

Number of Joysticks	Distribution Method	Path Type	Number of Targets	Average Completion Time (secs)
1	N/A	Simple	5	10.26
			10	14.02
1	N/A	Complex	5	10.40
			10	14.99
2	Dominant	Simple	5	19.22
			10	28.95
2	Dominant	Complex	5	19.90
			10	35.22
2	Non-Dominant	Simple	5	17.38
			10	23.12
2	Non-Dominant	Complex	5	15.42
			10	24.45

Table 3.10: Summary of results from the first experiment.

The results are displayed in the chart below.

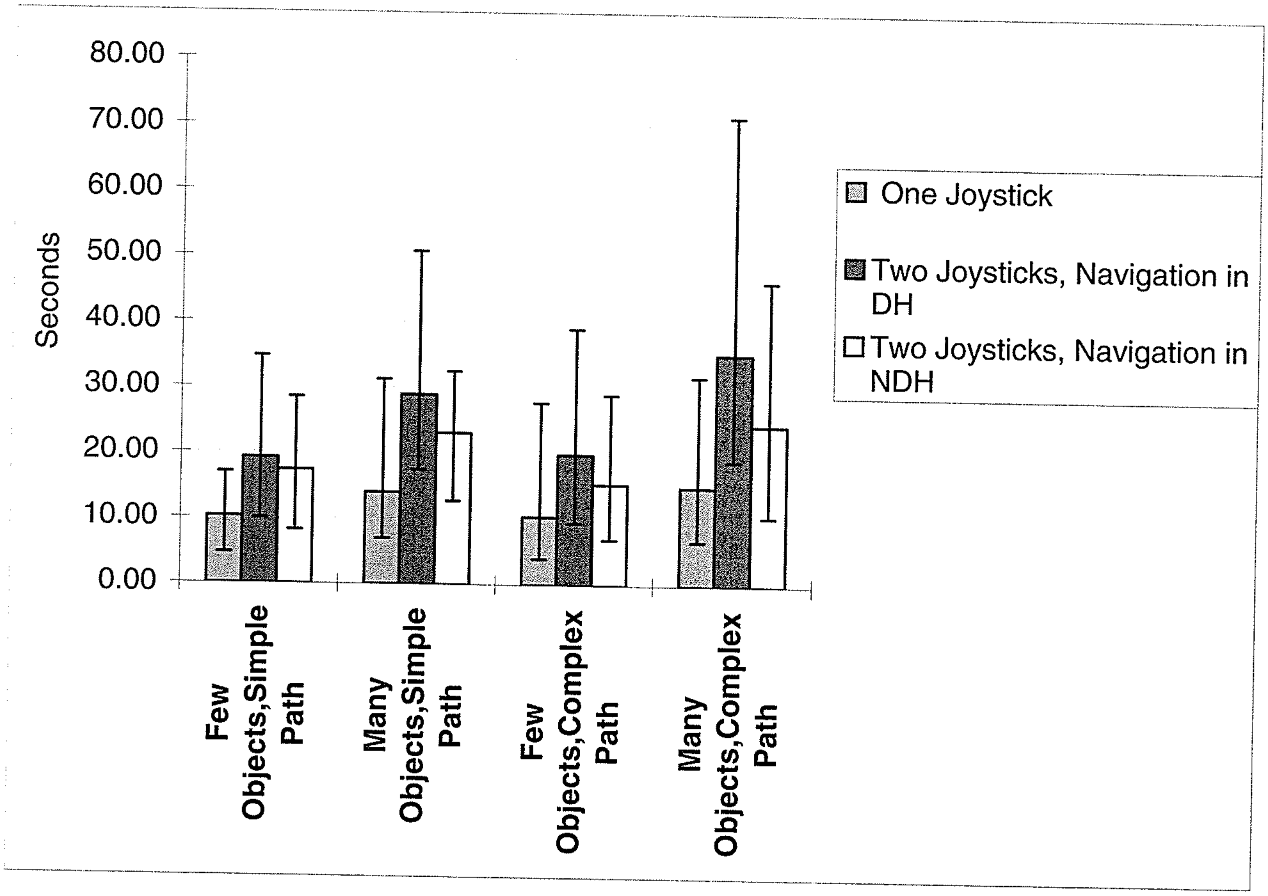


Chart 3.1: Summary of experiment 1 results. Unimanual outperformed both types of bimanual. However, comparing both bimanual techniques we observe that Guiard's theory is upheld.

The results are consistent across all participants for all experiment settings. In summary we see that:

1. Unimanual is faster than bimanual operation for all experimental settings. This is statistically significant ($p < 0.01$).
2. In the bimanual conditions, the non-dominant hand (NDH) navigation plus dominant hand selection performs faster than dominant hand (DH) navigation plus non-dominant hand selection. This is also statistically significant ($p < 0.05$).
3. The increase of the maze map complexity (path width and/or numbers of objects) results in longer completion times ($p < 0.05$).

4. In comparison to the impact of the complexity of the path type, the number of targets has a higher impact completion time.

3.2.2 Results of the second experiment

The results of experiment 2 are summarized in the table below.

Number of Joysticks	Distribution Method	Path Type	Number of Targets	Average Completion Time (secs)
1	N/A	Simple	5	7.78
			10	12.25
1	N/A	Complex	5	7.66
			10	10.67
2	Dominant	Simple	5	17.73
			10	27.91
2	Dominant	Complex	5	15.21
			10	23.991
2	Non-Dominant	Simple	5	13.361
			10	23.231
2	Non-Dominant	Complex	5	16.09
			10	20.86

Table 3.11: Summary of results from the second experiment.

These results are presented in the chart below.

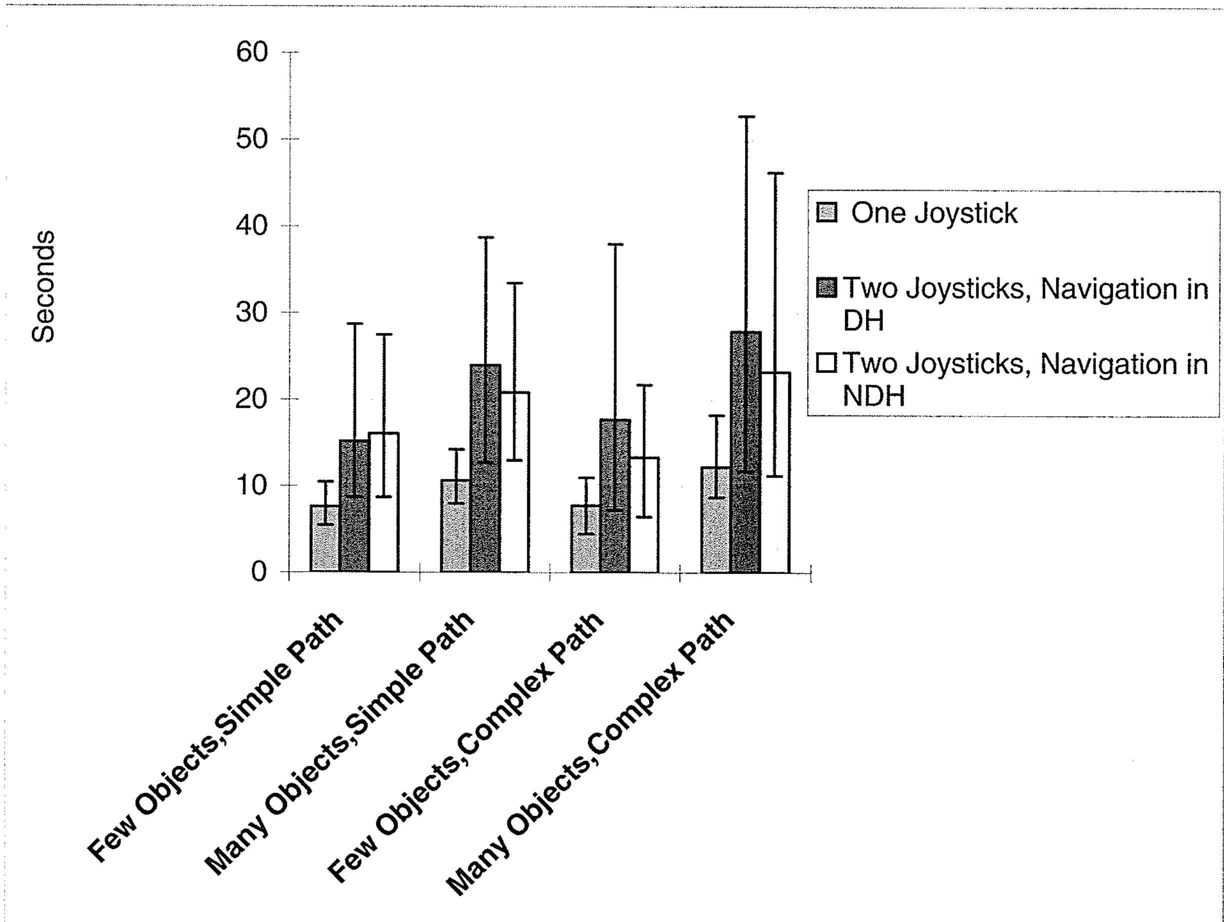


Chart 3.2: Summary of experiment 2 results. Unimanual outperformed both types of bimanual. However, comparing both bimanual techniques we observe that Guiard's theory is upheld.

Similar to the first experiment, with moving targets the experiment produced consistent results and reinforces the results obtained previously, namely:

1. Unimanual is faster than bimanual operation for all experimental settings.
2. In the bimanual condition, non-dominant hand (NDH) for navigation is faster than dominant hand (DH) for navigation.

3. The increase of path complexity (path width and/or target number) results in a longer navigation time. Compared to the impact of path complexity, the number of targets has a higher impact on average trial completion times.

All the results above were statistically significant at $p < 0.05$. The overall conclusions are similar for both the experiments and so I combine the discussion for these two experiments below.

3.2 Discussion

In the first two experiments, I found that unimanual operation performs better than when navigation is relegated to either the dominant hand or the non-dominant hand in bimanual experiments. These results show that:

1. Bimanual operations are not necessarily faster than unimanual operations when performing a composite task that may be sequential. Some tasks may be more efficient with unimanual operations, while others may be better operated with two hands. For this reason, before distributing labour to two hands it would be useful to establish a function for determining whether a task falls into a particular category of tasks.
2. The reason that unimanual operation outperforms bimanual operations in these experiments may be due to the fact that the utility of both hands may not be well optimized. In these experiments, the tasks of two hands are separated into two cursors. Although the results rely on the performance of both hands, each hand is not cohesively connected to the performance of the other. As a result this requires a higher cognitive load than when only one hand is in operation. Consequently, the time spent on both hands

is longer than on one hand only. To overcome this problem, when designing a bimanual operation strategy, designers should allow both hands to work together at the same time toward the same target. Then performance can be improved.

3. The strategy selected for bimanual operation is crucial to performance. From these two experiments, we can see that navigating using the non-dominant hand combined with selection using the dominant hand outperforms the opposite type of distribution. From users' feedback, I noted that the selection task is more difficult than the navigation task. In this case, selection requires the user to follow the navigation hand and then perform a precise selection on the object. This can be difficult given the complexity of the space users are required to navigate and select objects in. This result supports Guiard's model in that the non-dominant hand should be used for the coarser tasks, and the dominant hand should be responsible for the more precise task.
4. From the results in experiments 1 and 2, the manner of distributing tasks to unimanual or bimanual operation can have a significant impact on performance results. From these results I suggest the following guideline for designers: in composite tasks, categorize task attributes based on a sequential or parallel operation. Sequential operation refers to a single task composed of different phases and each phase occurring in temporal sequence with no simultaneity or overlap of events. The parallel task refers to a single task that needs to be performed concurrently by both hands. For parallel tasks, I categorize it as symmetrical parallel tasks and asymmetrical parallel tasks.
5. The experiments results show that when the task is sequential the unimanual technique would be the most efficient and simple method of operation. Bimanual operation would result in more complexity for both hands to collaborate as this requires a task switch and

handover, i.e. a take-over when the task is over and before the user starts proceeding to the next phase of the task. For parallel type tasks, bimanual techniques might be a better solution for conducting the task. However, a symmetrical parallel task implemented using bimanual operation could lead to significant deficiencies.

6. We can see the first group in the chart shows the average value of two-joysticks, with navigation on the NDH is a slightly higher than the average value of two-joysticks, navigation on the DH. According to the analysis of T-test, I can say that the average value of two-joysticks, navigation on the NDH is statistically smaller than the average value of two-joysticks. The reason for the average value of two-joysticks, navigation on the NDH is slightly higher than the average value of two-joysticks is that there are two subjects who used more time than the other subjects for some technical reason. This can be considered as a system error for this group of this experiment. However, it didn't affect the results for this experiment statistically. I compared all data I collected in this experiment, the result for every subject is consistent, and namely, two-joysticks with navigation on the NDH is faster than the average value of two-joysticks.

According to the analyses above, I conclude that:

- Bimanual interaction does not perform better than unimanual interaction for tasks that are sequential;
- Distribution of tasks to dominant and non-dominant hands depends on the workload required for the tasks and based on this and Guiard's theory one can then assign adequately the labour to each hand.

Chapter 4 – Dual-Cursor Navigation: A Technique Inspired by Guiard's Theory of Bimanual Control

The results from the previous two experiments show that Guiard's theory of bimanual control cannot be effectively applied to the tasks of simultaneous navigation and selection. However, when comparing the two different modes of bimanual interaction, from our results we observe that users feel highly fluent in their ability to navigate with the non-dominant hand and select with their dominant hand. This observation led to the design of a novel unimanual navigation technique inspired upon the idea of free-form navigation with the non-dominant hand and selection with the dominant hand. We refer to the novel unimanual technique as the dual-cursor navigation approach. The basic premise of the technique is that the user is provided two cursors, a *non-dominant cursor* and a *dominant cursor*. The non-dominant cursor is also referred to as the *virtual cursor* and the dominant cursor the *real cursor*. Based on Guiard's model of bimanual control we assign the following roles to each cursor in the dual-cursor navigation system (Table 4.1).

Cursor	Role and action of the cursor (based on Table 2.1)
Non-Dominant Cursor (Virtual Cursor)	- Leads the dominant cursor - Sets the spatial frame of reference for the dominant cursor - Performs coarse movements
Dominant Cursor (Real Cursor)	- Follows the non-dominant cursor - Works within the established frame of reference set by the non-dominant cursor - Performs fine movements

Table 4.1: Assignment of roles and actions to the dual-cursor technique. The assignment is largely based on Guiard's model.

4.1 Design of the dual-cursor system

The dual-cursor technique operates in a manner such that with very simple operations the user can use a virtual cursor that is projected out from the real cursor to "jump" over the constraints defined by the walls to inspect or view new areas without having to traverse all the navigation constraints. Once the virtual cursor reaches an object of interest, the user can trigger a "teleportation" to move the real cursor to join at the position of the virtual cursor.

To perform the navigation with the dual-cursor technique the user has to perform various mode shifts [11, 22]. Mode shifting is performed by manipulating several buttons on the input device, in this case a joystick. Several button configurations were implemented and piloted. I finally settled on the configuration explained below and described in figure 4.1. The user uses one hand and two fingers to carry out different operations including navigation, selection, activating the virtual cursor, combining the real cursor with the virtual cursor and restoring the real cursor's location. Button 1 is used for activating the virtual cursor. It is also used for returning back to the "home" position of the real cursor (explained below). Button 2 is used for restoring the virtual cursor to the real cursor spot. Button 3 is dedicated to the selection of objects.

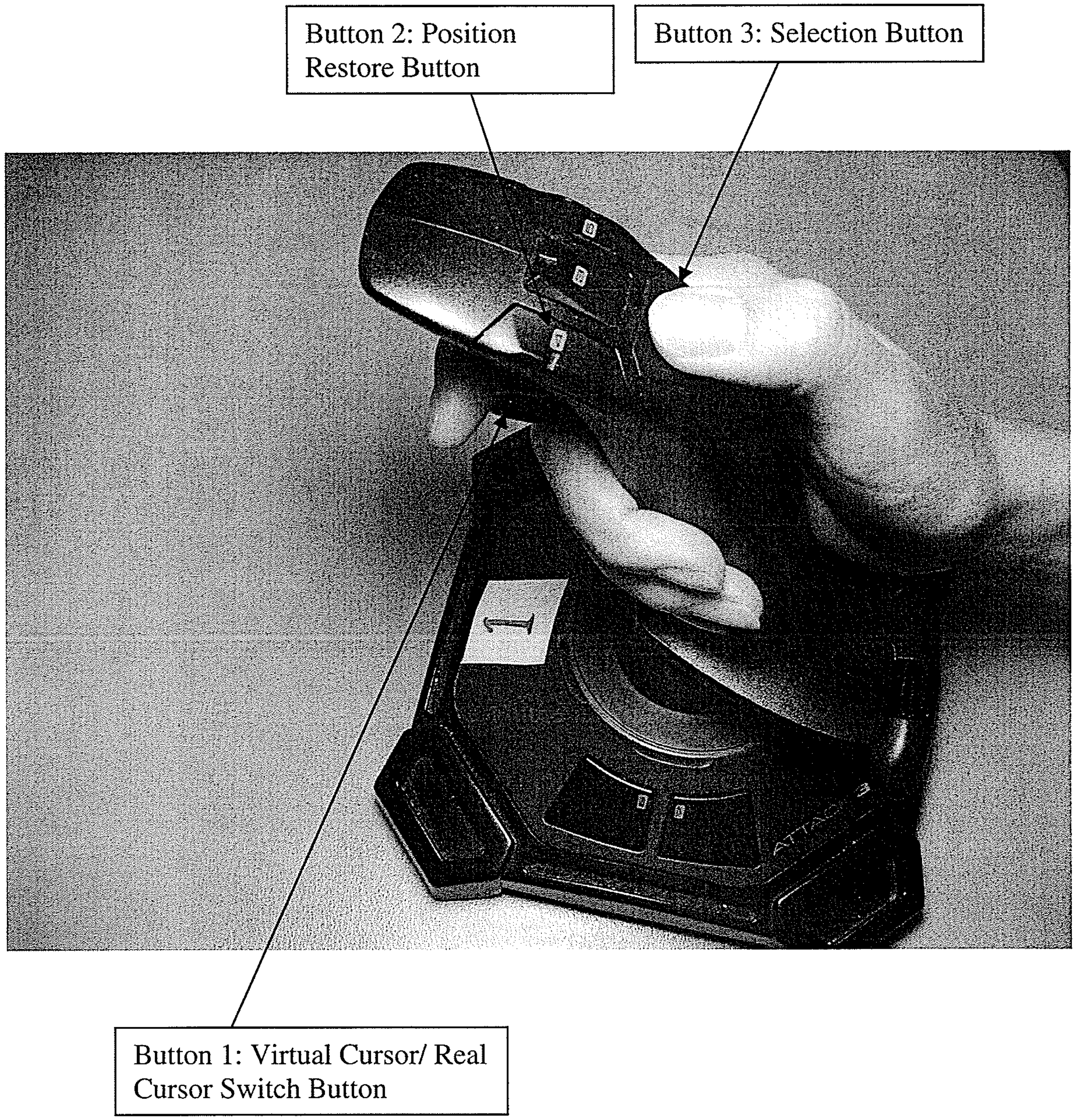


Figure 4.1: Joystick button mode optimization and configuration of buttons.

I explain in detail the mechanics of the dual-cursor technique by means of pictures along different steps of the navigation operation (figures 4.2 to 4.5). In figure 4.2, the user starts their navigation from the initial starting point (the left bottom corner of the map). When the user is interested in locating an object, he/she triggers button-1 on the joystick to activate the virtual cursor so that the virtual cursor can be controlled to "jump" over the constraints in the map (figure 4.3). When the virtual cursor arrives in the vicinity of the object of interest, the user releases the button 1 so that the real cursor coalesces with the virtual cursor. At this point the user can select the object of interest by clicking button 3. Meanwhile, if the player wants to return to the "home" location, he/she can press button 2 to ensure that the virtual cursor returns back to its original location or by the real cursor. This step is shown in figure 4.4. In figure 4.5, after the user selects the first of object of interest, he/she can proceed to navigate and find other objects in the scene by repeating the procedure depicted in figures 4.2 to 4.4. This process of navigation benefits the user in that the navigation is non-committal (unlike scrolling or panning, when the scene is shifted the user has to shift back again). The user can commit only when objects of interest have been found.

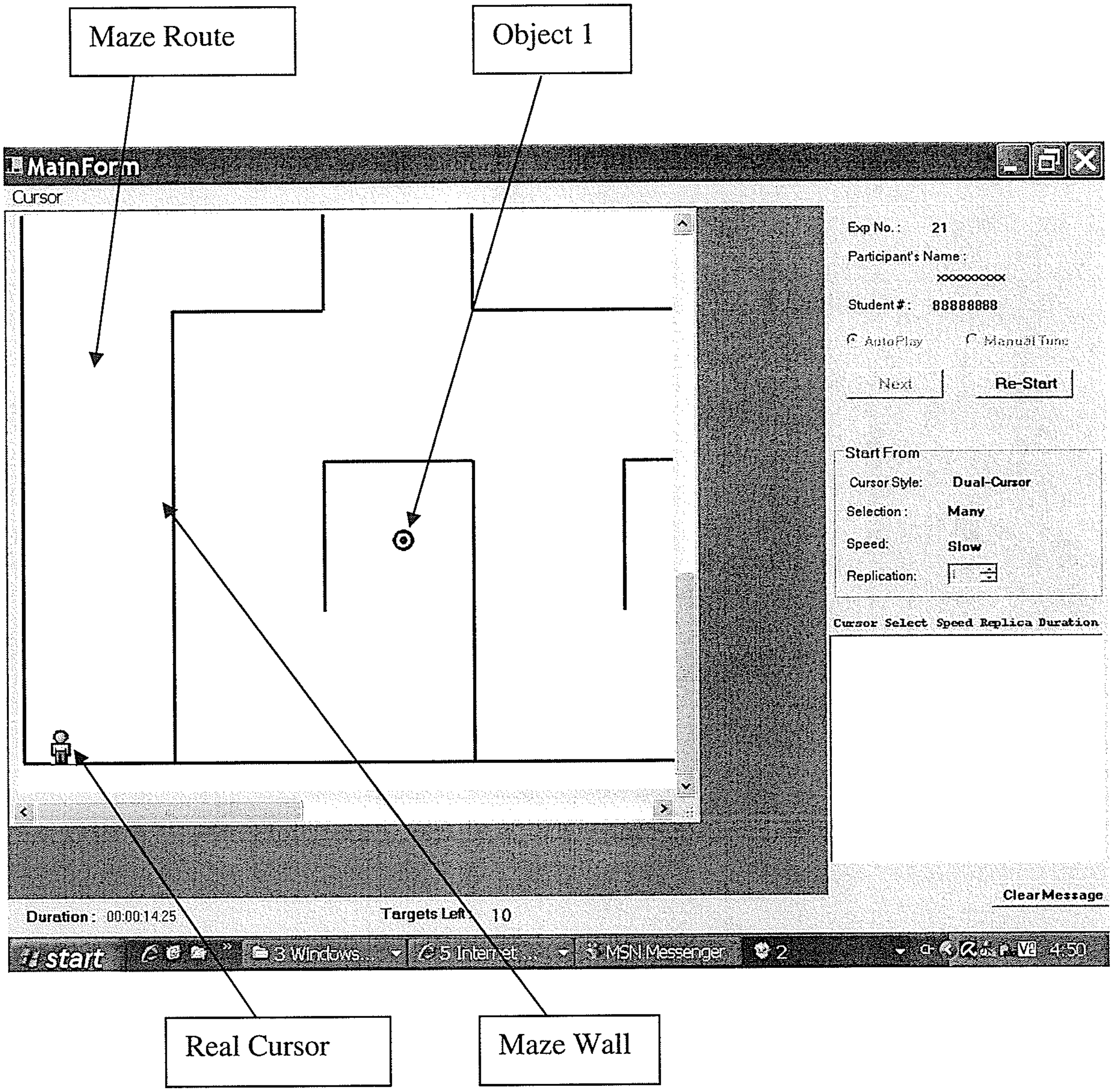


Figure 4.2: Initial position before triggering the dual-cursor technique. Only the real cursor is visible. The dual cursor becomes visible only when the user depresses a button on the input device.

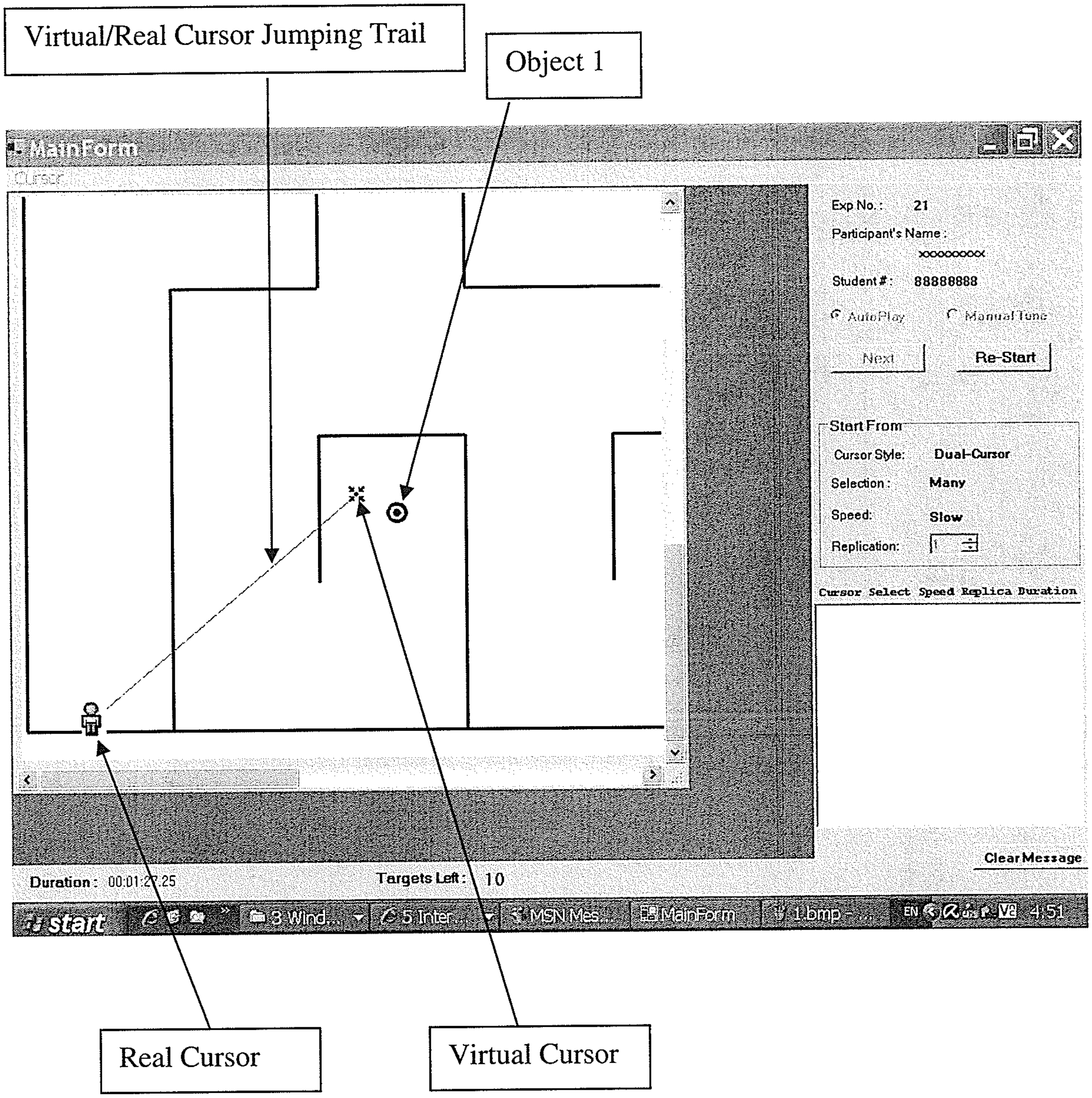


Figure 4.3: By pressing the proper button, the virtual cursor projects outward from the real cursor. With the joystick lever the user can control the virtual cursor to locate objects of interest in the scene. The virtual cursor is not restricted by the constraints of the scene.

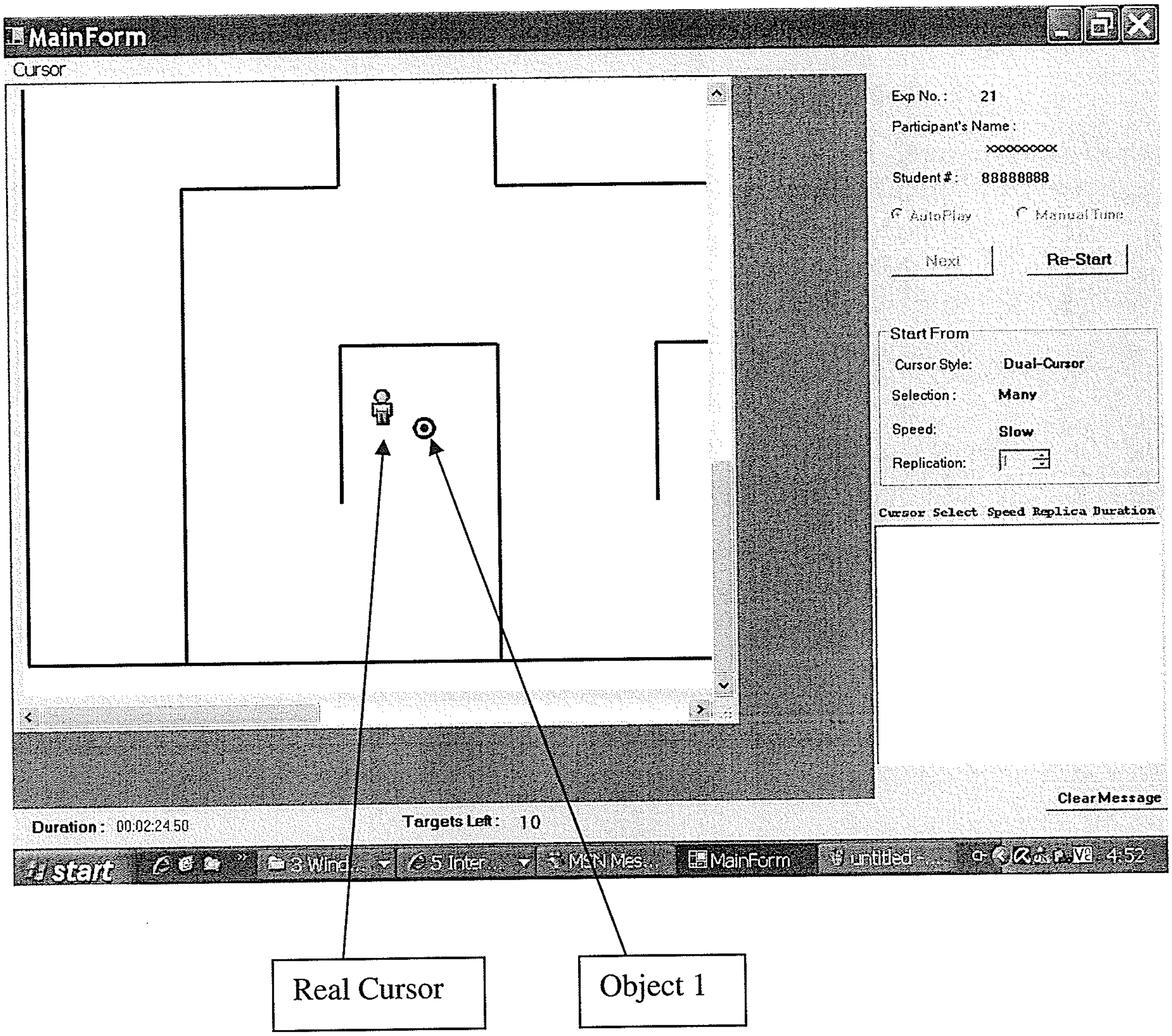


Figure 4.4: Once the user is satisfied with the location of interest, he/she can trigger a teleportation, which brings the real cursor to the vicinity of the virtual cursor. In this manner the user can jump around the scene.

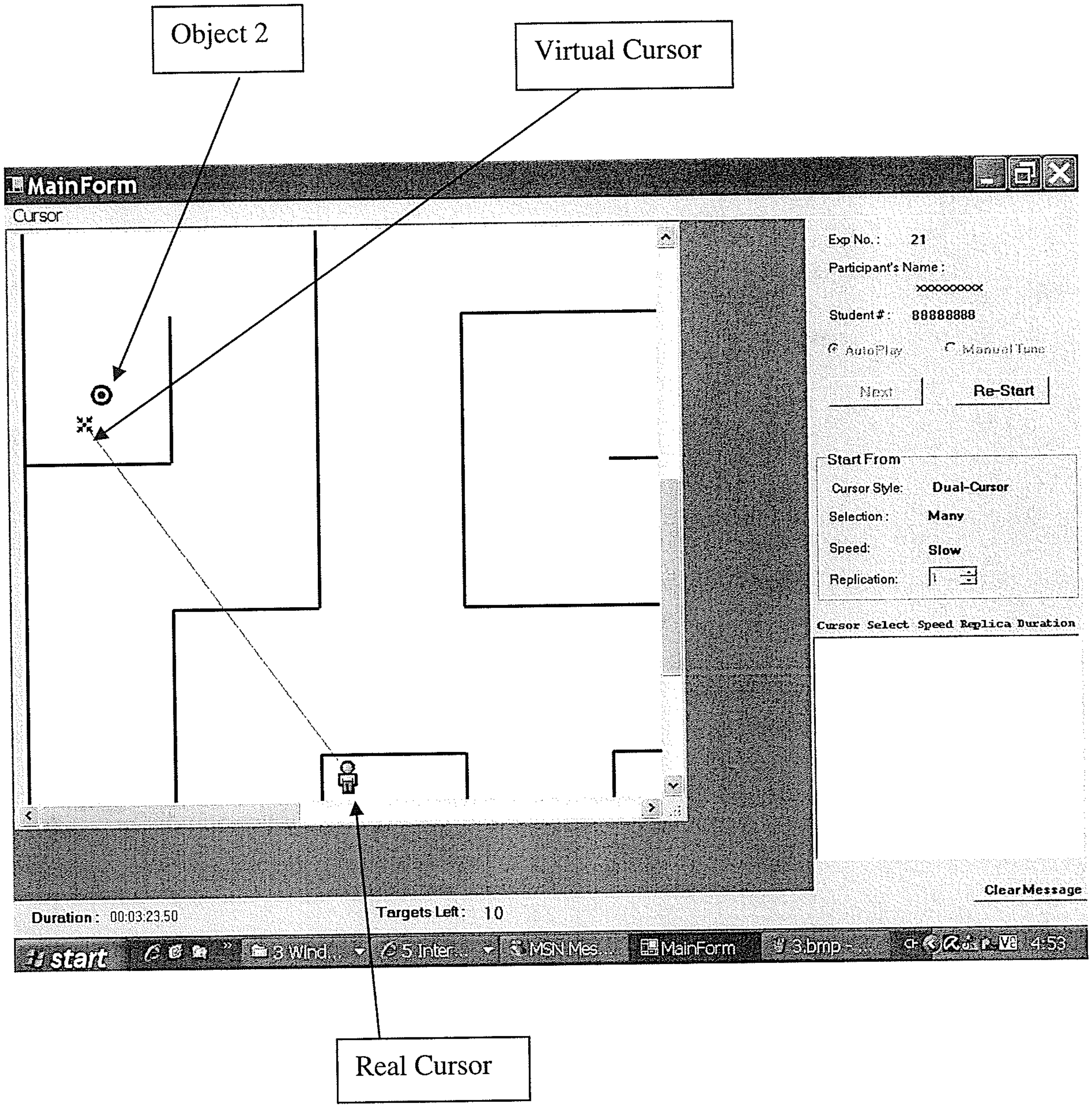


Figure 4.5: Dual-cursor initiated toward a new target.

4.2 Experimental Design

The purpose of this experiment was to evaluate the dual-cursor technique system in a constrained navigation system.

4.2.1 Materials and Implementation

The experiment was implemented on an Intel Pentium 4 CPU with a 20" 1280x1024 resolution display monitor. The operating system was Windows XP. The input device for navigation and selection is a Logitech Extreme 3D joystick. All the other materials are similar to those of experiments 1 and 2. Experiment 3 was also implemented using C#.NET.

4.2.2 Subjects

Ten participants were randomly selected to conduct this experiment. Subjects were volunteers from economics, computer science, engineering, business, arts departments or high school students. The following table shows related statistic information for subjects.

Age	15-20	20-30	30-40	40
Number	2	4	3	1

Table 4.2: Statistics of Participants Age

Gender	Male	Female
Number	8	2

Table 4.3: Statistics of Participants Gender

Background	Computer Science	Engineering	Economics	Arts	Business	High School
Number	2	2	2	2	1	1

Table 4.4: Statistics of Participants Background

Experience History	Yes	No
Use of Computer (Number)	10	0
Playing Game (Number)	10	0
Use of Joystick (Number)	4	6

Table 4.5: Statistics of Participants Experience History

4.2.3 Description of the task

The task is very similar to that of the experiments 1 and 2. The user is asked to navigate in a maze and look for objects to select. The maps are identical to those from previous experiments, but the locations of the objects are randomly placed. Also, the map is larger than the screen, thus the viewable area is only a portion of the full map. To perform the best comparison, all objects are set to each corner of the map, which requires that users perform their best to find the objects. This design is somewhat typical to the environments within which one would use these types of navigation (uni-cursor and dual-cursor) techniques. With the uni-cursor technique, the player has to navigate through the full map to find the targets. Without the dual-cursor technique, the cursor has to move along the route in the maze and reach the end of every route to find the objects.

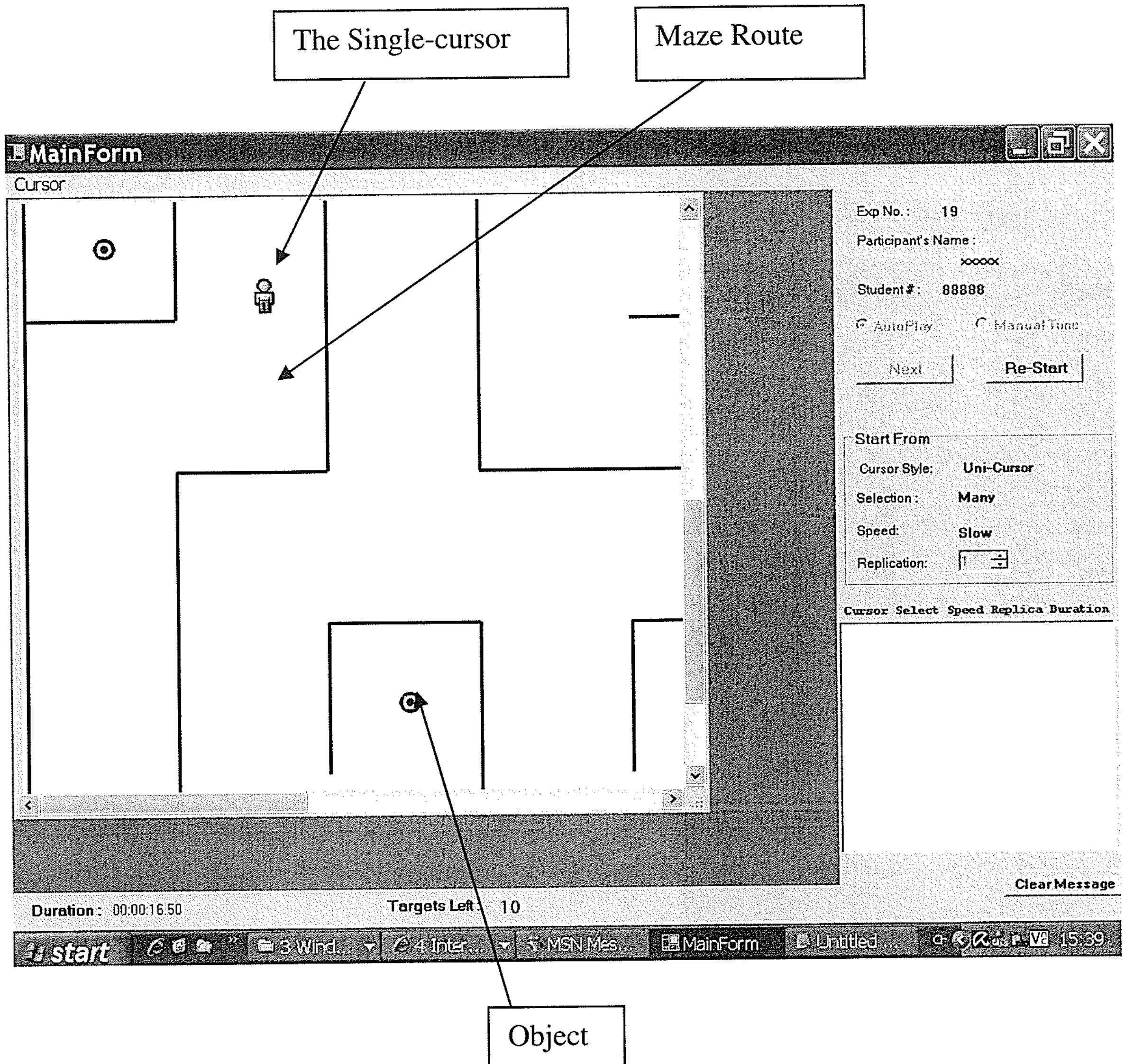


Figure 4.6: Uni-cursor regular navigation and selection.

4.2.4 Design

The experiment uses a 2x2x2 within-subject design. The main factors for this experiment are 3 levels shown as follows:

- Cursor type: uni-cursor vs. dual-cursor
- Cursor speed: slow vs. fast (2X speed of slow)

- Maze complexity (width of the maze path): simple vs. complex (1/2 paths width of simple)

4.2.5 Evaluation

For each trial the system records the time it takes the user to navigate and select objects in the entire maze. The experiment collects the completion time for each trial. Through both experiments, I compare the results and see whether the dual-cursor technique performs better than regular navigation.

4.3 Results and Analysis

The results of experiment 3 are summarized in Table 4.6.

Cursor Type	Speed	Number of Targets	Average Completion Time (s)
Uni-cursor	Slow	5	51.55
		10	59.18
Uni-cursor	Fast	5	40.65
		10	44.46
Dual-cursor	Slow	5	28.65
		10	37.29
Dual-cursor	Fast	5	24.51
		10	37.16

Table 4.6: Summary of results from experiment 3.

The Figure below shows the values obtained.

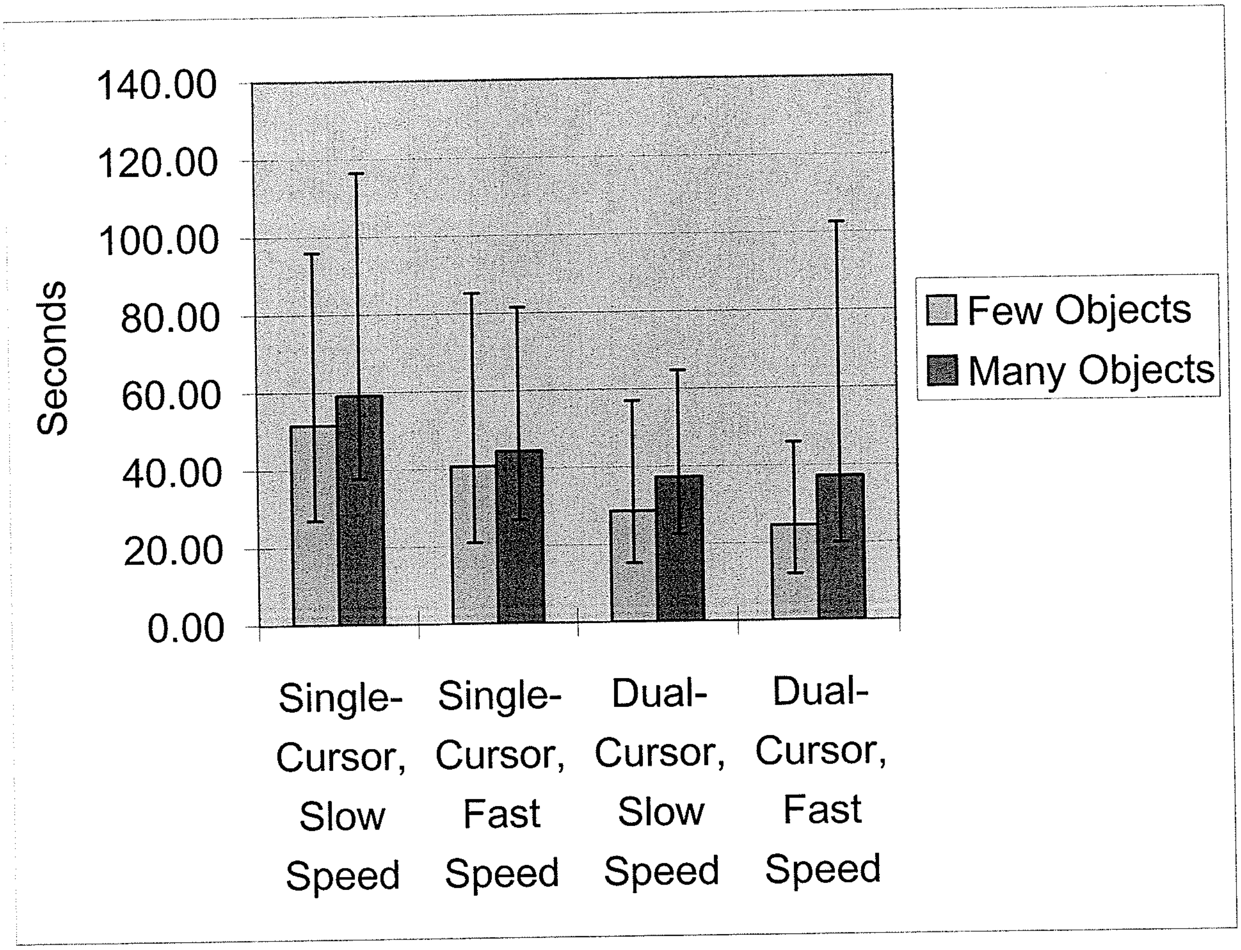


Chart 4.1. Chart of experiment 3 results

From experiment 3, we can see that,

1. The use of the dual-cursor technique (which is represented with dual cursor) highly improves performance ($p < 0.05$). When the cursor movement is slow or when the object

number is relatively small, the navigation time spent was reduced by nearly a half. This seems obvious since without having to walk along the maze path, the cursor can move faster to the target object. However, this is not exactly consistent in all cases. The general method for the uni-cursor system is performed by navigating through all the paths one by one to reach all places in the maze. The cursor has to enter every entrance in the maze to look for the objects. The general strategy for the dual-cursor system is to have the virtual cursor navigate row by row to cover all the locations in the scene. If all the target objects are ahead of the path for the cursor, then the cursor does not need to wander around to look for the objects. In this case, the uni-cursor technique is adequate for finding all the objects quickly. Using the dual-cursor technique might even bring an overhead because the path where the objects are located may not be along the rows being searched. If all the objects are outside the path of the cursor, then the uni-cursor navigation has to visit all the paths. In this case, the time spent in the non-dual-cursor system is optimal, since the dual-cursor can navigate through the constraints or "walls". In this experiment, the target objects are located in the latter manner. Thus, the use of dual-cursor technique greatly outperforms the uni-cursor system.

2. When there is only a single cursor, increasing the number of objects results in a slight increase of average completion times ($p < 0.01$). This is a result of the fact that for few-objects and many-objects conditions, the user always has to walk through all the paths, thus, the time used for navigation is not significantly different. More objects only lead to a bit more time used to select the additional objects.

3. When a virtual cursor (dual-cursor technique) is used, the increase in the number of objects results in longer completion times. This is obvious in that more objects require more time to find and select all of them ($p < 0.05$).
4. When a single-cursor is used, an increase of cursor speed reduces the time used to reach all the objects. This is because when increasing the speed, the users can walk through all paths in a faster manner ($p < 0.05$).
5. When a virtual cursor is used, the increase of cursor speed does not necessarily reduce the time used ($p < 0.01$). In contrast, when the number of objects is large, the users spend more time in the fast-cursor condition. This might be because when a fast-cursor is used, the user may move too fast and have very little control over the navigation method. As a result there are fewer opportunities to find the objects. This part of the performance varies significantly with the experience of the participants.
6. With the increase of cursor speed and number of targets, the experiment time for uni-cursor and dual-cursor searches get close to each other ($p < 0.05$). As indicated previously, the faster cursor speeds lead to less time spent on the uni-cursor system.

In finalizing the experimental design, I find the results comparing the uni-cursor to the dual-cursor are not very obvious when I use complete maps and configuration of objects as in experiments 1 and 2. The reason is that once the users misses an object, he/she has to return to a previously visited location to search for the object again and even may need to go through all the areas the cursor has gone through. However, it is hard for the user to miss objects in the scene using the uni-cursor technique. In such situations, the dual-cursor technique can be much slower than the uni-cursor navigation. Additionally, the cursor speed is an influential factor to the results when I alter the cursor moving speed to try and find the most optimal configuration. It is therefore essential that designers of such a technique test optimal speed ranges or provide users with the facility to configure their own cursor speeds.

Some very experienced users also commented that the convenience of discovering objects would be another factor that influenced the results. Finally, in some trials we see that the number of objects also affects performance rates. Increasing the number of objects means that the tester will take more time in the selection tasks than in navigation. As a result it may be that under such conditions the difference in effect between the dual-cursor and uni-cursor techniques would be minimal.

An interesting observation was that with one participant I noticed a drastically different navigation strategy. The user adopted a new navigation style. He did not follow other users' methods of navigating with the dual-cursor method. Instead he developed a super fast navigation approach, similar to a series of continuous "frog-jumps" to jump over the constraints in the scene. By using this method, the user was able to complete the experiment in half the time as that required by other participants. It may be that as a person gets more experience, he/she starts performing in radically different ways than anticipated and thereby tailoring navigation to their interaction styles. In future work, I am considering extending this technique to suit the approaches of navigation adopted by the participants. I believe that such a technique can facilitate regular navigation in current or newly developed applications.

Chapter 5 – Conclusions, Contributions and Future Work

I approached this thesis as a two-phase study with three distinct experiments to investigate the applicability of several theories to the task of constrained navigation and selection. The analysis of the results provides the following conclusions:

1. Experiments 1 and 2 validated Guiard's kinematics chain model of bimanual control for constrained navigation and selection tasks.
2. Bimanual operation is not necessarily more efficient than unimanual operation. The comparison would depend on the attributes of the task. For sequential tasks, unimanual operation should outperform bimanual operation. For asymmetrical parallel tasks, people would not be competent to finish this type of task in a bimanual operation mode. These types of tasks should be re-designed to sequential tasks or asymmetrical parallel tasks to benefit from bimanual operation. Only for symmetrical parallel tasks, bimanual operation would perform better than unimanual operation.

3. The dual-cursor navigation technique performs better than the uni-cursor technique in constrained navigation environments.
4. For the dual-cursor technique, there are some influential factors for its performance, such as different mode switching designs.
5. The dual-cursor technique is a novel navigation technique that can benefit from further extensive research and could be developed to work in other types of environments.

This thesis provides some contributions to the field of human-computer interaction.

1. This investigation validated Guiard's kinematics chain model of bimanual control for navigation and selection tasks in 2D constrained environments with input devices such as joysticks. This work has never been carried out before.
2. It extends the new concept of sequential and parallel attributes to the definition of different tasks for different hands and discusses how to assign and distribute workload to one hand or two hands.
3. In this research, the dual-cursor navigation technique is presented and applied in an environment requiring navigation and selection. After comparing dual-cursor to the uni-cursor technique, my experimental results show that the dual-cursor technique performs better. Under this experimental environment, some influencing factors that may affect the advantages of the dual-cursor navigation technique were discussed.

To extend this research, future work should include testing this design under different conditions. Also, to identify a criterion as to how to judge whether a task is more suitable for unimanual or bimanual control may require extensive study and tested in different conditions with various experimental designs.

My interest in this study has been to test the manner for workload distribution and find out a more efficient method to improve effectiveness for navigation and selection tasks. I have gained an understanding that regular navigation and selection methods are not convenient to all types of tasks. Novel techniques may be necessary. The dual-cursor is a prospective navigation technique that can handle the task under study. Further research is required to find various applications to the dual-cursor technique.

References

[1] Accot, J., and Zhai, S., Beyond Fitt's Law: Models for Trajectory-Based HCI Tasks, In Proceedings of the ACM conference on Human Factors in Computing Systems (CHI'97), 295-302, 1997.

[2] Balakrishman, R., Fitzmaurice G., Kurtenbach, G., and Buxton W., Digital Tape Drawing, In Proceedings of the ACM Symposium on User Interface Software and Technology (UIST'99), 161-169, 1999.

[3] Balakrishnan, R., and Hinckley, K., The role of Kinesthetic Reference Frames in Two-Handed Input Performance, In Proceedings of the ACM Symposium on User Interface Software and Technology (UIST'99), 171-178, 1999.

[4] Balakrishnan, R., and Kurtenbach, G., Exploring Bimanual Camera Control and Object Manipulation in 3D Graphics Interfaces, In Proceedings of the ACM conference on Human Factors in Computing Systems (CHI'99), 56-63, 1999.

[5] Bier, E. A., Stone, M. C., Poer K., Buxton W., and DeRose T., In James T, Kajiya. Toolglass and Magic Lenses: The see-through interface, In Proceedings of the ACM SIGGRAPH 1993 symposium on Interactive 3D graphics, 73-80, 1993.

[6] Buxton, W., and Myers, B. A., A Study In Two-handed Input, In Proceedings of the ACM conference on Human Factors in Computing Systems (CHI'86), 321-326, 1986.

[7] Carroll, J. M., HCI Models, Theories, and Frameworks toward a Multidisciplinary Science, Morgan Kaufmann Publishers, 2003.

[8] Chatty S., Extending a Graphical Toolkit for Two-Handed Interaction, In Proceedings of the ACM Symposium on User Interface Software and Technology, 195-204, 1994.

[9] Chatty S., Issues and Experience in Designing Two-Handed Interaction. In Proceedings of the ACM conference on Human Factors in Computing Systems (CHI'94), 253-254, 1994.

[10] Cutler, L. D., Frohlich, B., and Hanrahan P., Two-Handed Direct Manipulation on the Responsive Workbench, In Proceedings of the Symposium on Interactive 3D Graphics, 107-114, 1997.

[11] Dillon, R. F., Edey, J. D., and Tombaugh, J. W. 1990. Measuring the true cost of command selection: techniques and results. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems: Empowering People (CHI'90), 19-25, 1990).

[12] Fitzmaurice, G., Baudel t., Kurtenbach, G., and Buxton B., The Design of a GUI Paradigm based on Tablets, two-hands, and Transparency, In Proceedings of the ACM conference on Human Factors in Computing Systems (CHI'97), 35-42, 1997.

[13] Gold M., EaterGame II. http://www.csharpcorner.com/Code/2002/Oct/EaterGameII.asp, Oct. 2002.

[14] Guiard Y., Asymmetric Division of Labor in Human Skilled Bimanual Action: The Kinematic Chain as a Model, The Journal of Motor Behaviour, 19(4), 486-517, 1987.

[15] Hinckley, K., Czerwinski, M., and Sinclair M., Interaction and Modeling Techniques for Desktop Two-Handed Input, In Proceedings of the ACM Symposium on User Interface Software and Technology (UIST'98), 49–58, 1998.

[16] Hinckley, K., Pausch, R., and Proffitt D., Attention and Visual Feedback: The Bimanual Frame of Reference, In Proceedings of the ACM SIGGRAPH 1997 symposium on Interactive 3D graphics, 121-126, 1997.

[17] Hinckley, K., Pausch, R., Proffitt, D., Patten, J., and Kassell, N., Cooperative Bimanual Action, In Proceedings of the ACM conference on Human Factors in Computing Systems (CHI' 97), 27-23, 1997.

[18] Kabbash, P., Buxton W., and Sellen A., Two-handed input in a compound task, In Proceedings of the ACM conference on Human Factors in Computing Systems (CHI'94), 417-423, 1994.

[19] Latulipe, C., Kaplan, C. S., and Clarke, C., Bimanual and Unimanual Image Alignment: An evaluation of Mouse-Based Techniques, In Proceedings of the ACM Symposium on User Interface Software and Technology (UIST'05), 123-131, 2005.

[20] Latulipe, C., Laplan, C. S., and Clarke, C., Mouse-based Rotation and Translation, In Proceeding of Human-Computer Interaction (HCI'05), 63-67, 2005.

[21] Leganchuk, A., Zhai, S., and Buxton W., Manual and cognitive benefits of two-handed input an experimental study, ACM Transactions on Computer-Human Interaction, 5(4), 326-359, 1998.

[22] Li, Y., Hinckley, K., Guan, Z., and Landay, J. A. 2005. Experimental analysis of mode switching techniques in pen-based user interfaces. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '05), 461-470, 2005.

[23] MacKenzie, I. S., and Guiard, Y., The Two-handed Desktop Interface: Are we there yet? In Proceedings of the ACM conference on Human Factors in Computing Systems (CHI'01), 351-352, 2001.

[24] Owen, R., Kurtenbach, G., Firzmaurice, G., Baudel T., and Buxton B., When it gets more difficult, use both hands – exploring bimanual curve manipulation, In GI 2005 proceedings, Graphics Interface 2005 - Canadian Human-Computer Communications Society, 17-24, 2005.

[25] http://www.pcmag.com/encyclopedia_term/0,2542,t=telesurgery&i=52712,00.asp

[26] Zeleznik, R., Forsberg, A., and Strauss, P., Two Pointer Input For 3D Interaction, ACM I3D Symposium on Interactive 3D Graphics, 115-120, 1997.

Appendix: T-test

The *t*-test is a method of comparing two randomized groups of data and analyzing the statistical difference between them. Assuming the variances between the two groups are equal, we can use their means, standard deviations and the number of data points to conduct a *t*-test and determine the level of distinction between the two populations.

When performing a *t*-test, I first need to calculate a probability value, which is also called *p*-value or *t*-value. The *t*-value represents the probability of having a Type-II Error, i.e. when we conclude a hypothesis is true while it is indeed not true. There is a table of significance, called *t*-table, to determine the level of confidence that our conclusions are correct. If the *t*-value is smaller than 0.05, it indicates the possibility of have a Type-II Error is less than 5%. Thus, we have a 95% confidence that the conclusion is correct. Therefore, we should always like to have the t-value as small as possible. Generally, we consider a difference between means at the 95% level as "significant", a difference at 99% level (where $t = 0.01$) is "highly significant" and a difference at 99.9% level (where $t = 0.001$) is "very highly significant".

We should note that this *t*-test provides a conclusion from statistical point of view, but not as a proof, where a proof indicates a 100% of confidence. With a 95% confidence, there is still a one out of 20 chance the conclusion is wrong. In this research, I accept 95% confidence as an acceptable level.

The *t*-Test Procedure

Assuming the two groups are called group 1 and group 2. We first need to list the data from both groups, and the number of data (represented as n_1 and n_2 respectively) in each group. Then, we calculate their means (denoted as $\bar{x}_1$ and $\bar{x}_2$) and their standard deviations (s_1^2 and s_2^2). After that, we calculate the variance between the two standard deviations using the following function. This variance is represented as sd^2.

$$\sigma_d^2 = \frac{\sigma_1^2}{n_1} + \frac{\sigma_2^2}{n_2}$$

Using sd^2, we can obtain sd, which is the square root of sd. Then with the following function, we can calculate the *t*-value:

$$t = \frac{\bar{x}_1 - \bar{x}_2}{\sigma_d}$$

In order to obtain a positive value, when performing the subtraction between the two means, we should keep using the larger value to subtract the smaller value, Thus, if $\bar{x}_2 > \bar{x}_1$, we would exchange the position of $\bar{x}_1$ and $\bar{x}_2$. At the end, we use ($n_1 + n_2 - 2$) as the degrees of freedom, select the expected level of significance (e.g. p=0.05), and read the tabulated t value. If the calculated *t*-value exceeds the tabulated value then the means are significantly different.