Multimodal Virtual Environments: MAGIC Toolkit and Visual-Haptic Interaction Paradigms

by

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B.S., Mechanical Engineering (1995)
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Chapter 1

Introduction

1.1 Virtual Environments

Virtual Environments (VEs) are computer generated worlds that give humans a means to design and experience events that would otherwise be impossible, difficult, expensive, or dangerous in a real environment. Proposals for the use of VEs fall into four main categories: 1) teaching and training, 2) health care, 3) design and manufacturing , and 4) entertainment. For the first category, VEs allow simulation of training programs such as piloting or performing surgery. This type of application allows potential pilots or doctors to practice and perfect techniques in their respective fields with impunity should anything go wrong. The potential pilot would not endanger himself/herself, any passengers, or the aircraft in a VE simulation, neither would the medical student endanger the life of a patient. Training in an artificial environment of an actual or hypothetical situation allows the person to learn the correct procedures and techniques of a given task.

In health care, VEs could potentially diagnose or track the recovery status of a patient with a standardized test that would stimulate and record specific reactions. In the commercial industries of design and manufacturing, VEs could be used to design and test structures or products. This type of simulation saves on time and materials involved in constructing or manufacturing. In the entertainment industry, VEs can simulate imaginative scenarios for people to play in. The quality of a VE can be measured based on how "immersed" a person feels. If a VE can deceive the human senses into believing that the environment he/she is in is real, the person will feel immersed in the environment.

Humans have five primary senses to perceive their surroundings: sight, sound, touch, smell, and taste. The three main modalities humans use to interact with and navigate through the real world are sight, sound, and touch. The human vision and audition systems are purely sensory in nature; in contrast, the human haptic system, which includes the human sense of touch, can both sense and act on the environment [Srinivasan, 1994]. There has been a great deal of research about the human visual and auditory system. Facts discovered about these modes of perception have aided the development of visual and audio interfaces. The availability of visual and audio interfaces coupled with computer control and technology allow for the rapid progress of these aspects in the design of VEs. Computer graphics has evolved to a state where images presented has an uncanny likeness to a real object. Audio devices can now output sounds with amazing fidelity to the original environment in which the sound is recorded. Compared to what is known of the human vision and audition, understanding of human haptics is still very limited, yet the ability to haptically explore and manipulate objects is what greatly enhances the sense of immersion in VEs[Srinivasan, 1994].

Haptics, in the context of VEs, have two intrinsically linked categories: human haptics and machine haptics. The development of machine haptics allow for experiments on human haptic abilities and limits. By knowing human haptic abilities and limits, haptic interfaces can be improved and designed to enhance the sense of touch. Figure 1-1 depicts the categories of haptics and the relationship between human haptics and machine haptics.

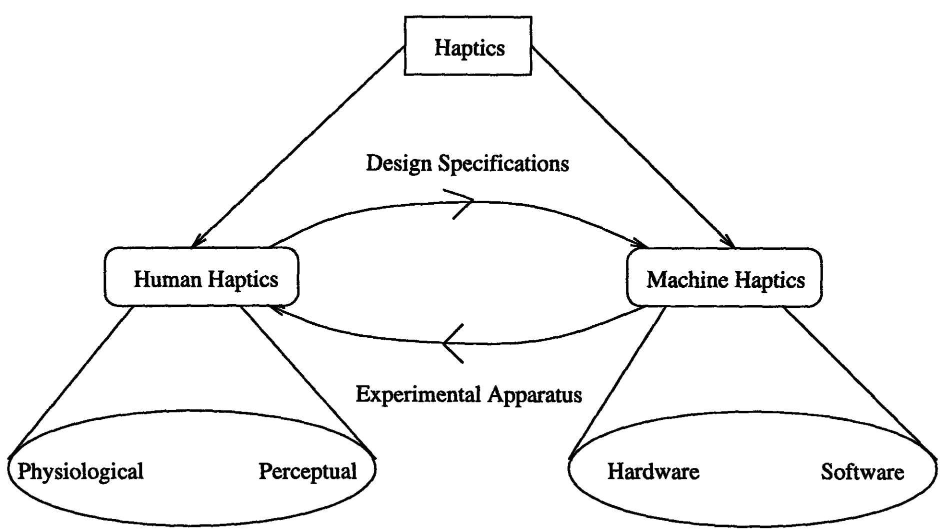


Figure 1-1: Haptics Tree

1.2 Human Haptics

The study of human haptics has two aspects: physiological and perceptual. The goal of physiological haptics is to understand the biomechanical and neural aspects of how tactual sensory signals as well as motor commands are generated, transmitted, and processed. The goal of perceptual haptics is to understand how humans perceive with the tactual sense: the methods and levels of accuracy for detection, discrimination, and identification of various stimuli.

Human tactual sensing can be divided into two sensory modes, kinesthetic and tactile. Kinesthetic refers to the sensing of position, movement, and orientation of limbs and the associated forces with the sensory input originating from the skin, joints, muscles, and tendons. Tactile sensing refers to the sense of contact with an object. This type of sensing is mediated by the responses of low-threshold mechanoreceptors near the area of contact[Srinivasan, 1994]. The tactual sensing in combination with the human motor apparatus in the haptic system allow humans to use their hands to perceive, act on, and interact with their environment.

Quantitative research has discovered several facts about the human haptic system:

- Humans can distinguish vibration frequencies up to 1 KHz through the tactile sense.
- Humans can detect joint rotations of a fraction of a degree performed over about a second.
- The bandwidth of the kinesthetic system is estimated to be 20-30 Hz.
- The JND (Just Noticeable Difference) for the finger joint is about 2.5 degrees, for the wrist and elbow is 2 degrees, and about 0.8 degrees for the shoulder.
- A stiffness of at least 25 N/mm is needed for an object to be perceived as rigid by human observers. [Tan et. al., 1994]
- The JND is 20% for mass, 12 % for viscosity, 7% for force, and 8% for compliance[Beauregard, 1996].

In addition to finding out how humans react to different stimuli, how they perform with different interfaces, and how they react in different environments, insight into what feels natural to them and what types of interfaces may be suitable for different tasks is also needed. Understanding human haptic abilities and limitations can lead to improvements of current haptic devices and the development of new devices which will give the user a more immersive experience.

1.3 Machine Haptics

The development of machine haptics is composed of hardware development and software development. Haptic interfaces allow humans to interact with the computer. This interaction requires a physical device to transmit the appropriate stimuli and software to control the stability and desired action and reaction.

1.3.1 Haptic Hardware Development

There are three categories of haptic interfaces: tactile displays, body based devices, and ground based devices[reviewed by Srinivasan, 1994]. Tactile displays stimulate the skin surface to convey tactile information about an object. Research into this area has primarily focused on conveying visual and auditory information to deaf and blind individuals[Bach-y-Rita, 1982]. Body based devices are exoskeletal in nature. They could be flexible, such as a glove or a suit worn by the user, or they could be rigid, such as jointed linkages affixed to the user. One such device is the "Rutgers Master II", which uses four pneumatic cylinders with linear position sensors in addition to a rotary sensor to determine the location of the fingers and actuate a desired force[Gomez, Burdea, Langrana, 1995].

Ground based devices include joysticks and hand controllers. One of the first force-reflecting hand controllers was developed at the University of North Carolina with the project GROPE, a 7 DOF manipulator [Brooks et al., 1990]. Margaret Minsky developed the Sandpaper System, a 2-DOF joystick with feedback forces that simulates textures. [Minsky et al., 1990] The University of British Columbia developed a 6 DOF magnetically levitated joystick which features low-inertia and low friction [Salcudean, 1992]. MIT's Artificial Intelligence Laboratory developed the PHANToM. It features three active degrees of freedom and three passive degrees of freedom with a point contact which has low inertia and high bandwidth[Massie and Salisbury, 1994].

This thesis discusses the development of a software application designed to be used with the PHANToM, but can be applied to any point-interaction haptic interface device which outputs a force given a position.

1.3.2 Haptic Software Development

The development of haptic interfaces has resulted in a need for increased understanding of the human haptic system. The growth of this field has also found some problems and limitations in the performance of haptic devices. Due to the inherent nature of haptics, all computations must be calculated in real-time. Given the fact the VEs are enhanced with the combination of visual, auditory, and haptic stimuli, a substantial amount of computational power is required to run a multi-modal VE in real-time. The development of efficient code and methods of rendering in the three main interactive modalities is essential for a quality simulation. Since motors can only generate a finite amount of torque over certain periods of time, methods of rendering scenes which will give the illusion of a stiff surface are needed. The software development can possibly compensate for hardware limitations and make the virtual world feel more natural. Since the virtual world does not have to obey all the laws of the physical world, software development can also create effects that are not possible in a real environment.

Studies on the software requirements for stiff virtual walls have been conducted at Northwestern University[Colgate, 1994]. It is possible for a user to touch one side of a thin object and be propelled out the opposite side, because surfaces are usually rendered using an algorithm which output a force proportional to the amount of penetration into a surface. This motivated the development of a constraint based algorithm which keeps a history of the cursor's surface contact and outputs the force in a direction normal to the contact surface[Zilles and Salisbury, 1995]. Displaying a deformable object gives the user an illusion of a soft object[Swarup 1995]. This method of rendering compensates for a device's motor torque limit, since the visual presentation of a deformed object implies an intentional non-stiff object. A study in visual dominance has found that when a user is presented with two virtual springs and asked to determine which of the two is stiffer, the user will almost always choose the spring that visually compresses less for a given force and ignore the haptic dependent cues[Srinivasan et. al., 1996]. Force shading is a method that maps a pre-specified radial vector to a planar surface in order to create the haptic illusion of a curved surface when a planar surface is displayed[Morgenbesser and Srinivasan, 1996]. This method is useful in creating complex curved objects. One could render a polyhedral mesh that describes an angular object, add force shading, and create a perception of a smooth curved object. This would reduce computation time since it is simpler to specify a polyhedral approximation to a curved surface than it is to specify a continuously smooth complex object.

With the development of haptic interfaces comes the development of software for use with the device. First basic algorithms need to be developed to control the device. Next it must be able to render virtual objects or scenes accurately. Once these basic needs are satisfied, the device can be used in a higher level application. To facilitate the end goal, it would be useful to have a development environment to create virtual scenes. This thesis describes the development of a software toolkit to facilitate the creation of multimodal virtual environments.

Increased understanding of human haptics, improved rendering techniques, and better haptic interfaces in combination with visual and auditory developments will allow multimodal virtual environments to reach a state where complex applications such as surgical training can be realized.

1.4 Contributions to Multimodal Virtual Environments

The goals of this thesis are to develop applications and investigate interaction variations that would help in the expansion of the use of multimodal virtual environments. Key factors that play a role in how quickly and easily a new field, such as multimodal virtual environments, becomes widespread, are cost and ease of use.

A system which is capable of rendering high quality multimodal virtual environments will most likely be very expensive. The intrinsic nature of this immersive technology requires real-time updates of the visual, haptic, and audio environment. The updates require a significant amount of computing power. For the graphics rendering, an usual setup is to have a Silicon Graphics machine or a PC with a graphics accelerator running 3-dimensional scenes generated with OpenInventor. This type of system commonly costs at least $10,000.

The physical hardware of a haptic device is also needed for manual interaction with the virtual environments. A device, such as the PHANToM, costs about $20,000. In addition, computational power is required to interpret the location and control the force feedback. Depending on the computational power of the graphics systems described above, the haptic computations can be on the same system, or may require a separate processor. The necessity of another processor adds to the cost of the complete system. The same arguments can be applied to the addition of the audio aspect of the multimodal VE.

A high quality multimodal VE rendering system can very quickly become very expensive. There are several applications of VEs which do not require the highest fidelity of performance in all sensory modes. In this thesis, the goal is to develop an application which focuses on high fidelity haptics and adequate graphics for a single processor system. This basic type of VE rendering system allows for the fundamental studies on the human haptic system and on human interaction with multimodal VEs. This system is relatively simple and inexpensive; it requires only a PC and a haptic interface device, such as the PHANToM.

To make such a system easy to use, the MAGIC Toolkit has been developed. It includes an application program and a set of library files that allows an user to easily create 3-D haptic and 2-D visual environments. The application has object primitives in which the user can use like building blocks to create a scene. These objects have attributes such as size, location, stiffness, and color, which can be readily be changed with a touch to the menu.

This "Building Blocks" type of application makes the creation of multimodal VEs simple even for the novice user, and affordable. The availability of an effective and affordable system, increases the viability of the growing use of multimodal VEs. A large base of users creates a platform in which more applications can be created and a better understanding of interactions can be achieved.

In addition to the development of the MAGIC Toolkit, this thesis also describes the use of the Toolkit in creating mazes for a series of human visual-haptic interaction experiments. These experiments study the performance and preference of users when different size visual and haptic displays are presented. Other parameters that are varied include different objectives for completing the maze, different levels sensory feedback, and different cursor control paradigms. In some experiments the subjects are told to optimize speed, in others, to optimize accuracy. Some experiments varied the size of both the visual and the haptic display, while other experiments varied only the size of the visual display. The sensory feedback experiments consist of three sessions in which the subjects are presented at first with both visual and haptic feedback, then with only haptic feedback, and finally with only visual feedback. Another set of experiments investigates the effects of cursor control differences between position control and force control.

The larger goal of this project is to make multimodal VEs simple, effective, easy to use, and affordable so that it can be incorporated into many applications. This project also aims to achieve a better understanding of the human visual-haptic interaction.

The following list summarizes the contributions made in this thesis to the field of multimodal virtual environments:

- developed the MAGIC Toolkit, a VE building blocks application and library file for a single Pentium processor PC system which has both visual and haptic rendering.
- developed a menu driven program to be a) user friendly, and b) easy to change attributes of objects.
- developed an organized structure for object characteristics that users can easily access and add information about the attributes of the object.
- developed a novel rendering algorithm that allows for a speedy calculation of forces for a cone.
- defined various human visual-haptic interactions.
- conducted experiments to study the effects of visual and haptic size on user preference and performance.
- conducted experiments to study the effects of visual and haptic feedback on user preference and performance.
- defined various cursor control paradigms.
- conducted experiments to study the effects of various cursor control paradigms on user preference and performance.
- found that subjects perform best with and prefer a large visual workspace paired with a smaller haptic workspace.
- found that subjects perform best with both visual and haptic feedback.
- found that subjects prefer position control cursor paradigms to force control cursor paradigms.
- found that an illusion of having stiffer walls can be created using a haptic workspace that is larger than the visual workspace.

1.5 Overview

To help the reader with the organization of this thesis, the following is a summary of what is presented in each chapter.

- Chapter 2 discusses the development of the MAGIC Toolkit. This DOS-based toolkit facilitates the creation and editing of complex virtual scenes and complex virtual objects. A description of how object primitives are used to build the scene is followed by a discussion of the various characteristics of each object. An innovative way to render a cone is described. A description of the library files is given.

- Chapter 3 discusses several visual-haptic interaction paradigms. Size ratios of the visual workspace to the haptic workspace and their effects on users' perception of the environment are investigated. One set of variations has a combination of two visual workspace sizes and two haptic workspace sizes. The other set of variations has one haptic workspace size and four visual workspace sizes. Cursor control is another important aspect of user interaction. Four different types of cursor control paradigms are discussed including two position control and two force control cursor paradigms.

- Chapter 4 describes the experimental methods used to investigate the effects of different visual-haptic interaction paradigms. One set of experiments investigates user preference and performance, given different visual-haptic workspace ratios. It also investigates the performance when given different objectives for completing the maze, for example, speed vs. accuracy. The role of sensory feedback is also investigated. Subjects were presented with the maze with both haptic and visual feedback, with haptic feedback but without visual feedback, and without haptic feedback but with visual feedback. Another set of experiments investigated training effects. The performance of subjects who trained on a large visual workspace is compared with the performance of subjects who trained on a small visual workspace. The former describes the effects of decreasing visual scaling, the latter describes the effects of increasing visual scaling. The final experiment tested subjects on the performance and preference of the cursor control paradigms. In this set, they were given a single visual size that corresponded to the haptic size.

- Chapter 5 presents the results of the experiments. Subjects prefer and perform best on a large visual display and a small haptic display. Results show that subjects perform best when given both visual and haptic feedback. Their performance decreased by 26% when given only haptic feedback, but decreased over 61% when given only visual feedback. In the visual scaling experiments, subjects performed consistently when they trained on a large visual display. They performed less consistently when they trained on a small visual display. In the cursor paradigm experiment, subjects preferred position control over force control paradigms. They also completed the maze faster with the position control paradigms.

- Chapter 6 discusses the significance of the results of the experiments. Subjects prefer and perform best on a large visual environment with a small haptic environment. Presenting a small visual environment coupled with a large haptic environment gives the illusion of very stiff walls. Having both visual and haptic feedback gives rise to the best performance. When only one sensory mode is given, performance is better with only haptic feedback than with only visual feedback. Training on a visual environment larger than the haptic environment results in a linear improvement in time performance when the visual environment is increased as the haptic environment remains at the same size. There is a limit to the improvement in time performance when a subject is trained on small visual and haptic environment. In fact, the performance of some subjects actually degrade at larger visual-haptic size ratios. Subjects find position control cursor paradigms easier than force control. Performance is better when there is a high correlation in motion and force between the visual and haptic realms.

- Chapter 7 concludes with an evaluation of the application toolkit and experiments. It also discusses directions for future work. The sample size of subjects for the experiments is small, but representative. This study shows the general trends of performance. Continuing this study with more subjects could more accurately specify the degree to which these trends are true. It would also be interesting to conduct a similar series of experiments with much smaller haptic workspaces to study human fine motor control.

Chapter 2

The MAGIC Toolkit

2.1 Motivation

The current methods of creating virtual environments are not very user friendly, especially to users who are not familiar with the field of haptics. These methods require the user to manually program the specific shapes, sizes, and locations of the objects, or to draw the desired virtual scene in another application, such as CAD or FEA, then have a program that translates the file into a form that is suitable for a haptic display. These time consuming and user un-friendly methods prompted the development of the MAGIC Toolkit, a software application program and library which would allow users to easily create and edit complex virtual objects or scenes. This virtual "building blocks" program is easy to use for both the low level user and the high level user. The novice can use the menu driven program as a creation medium. This user can add objects to the scene to view and touch. The high level user has a goal of using the scenes created in the menu driven program for a complex application. This user can employ the library of functions to help in the manipulation of the scene in the programming.

The MAGIC Toolkit has a collection of object primitives that the user can employ to create VEs or complex virtual objects. It organizes the visual and haptic characteristics of objects in a structure which facilitates the visual and haptic presentation of the VE. Designed to be used with the PHANToM haptic interface device, the MAGIC Toolkit allows the user to see, manually feel, create, and edit a virtual environment.

2.2 Apparatus

The MAGIC Toolkit is designed to be used with a point interaction, open loop control haptic interface that outputs a force for a given position. The PHANToM, shown in Figure 2.1, has three active degrees of freedom (x, y, z) and three passive degrees of freedom (θ, ϕ, ψ). The stylus at the end of linkage is a pen-like device that the user holds to explore the haptic workspace. The MAGIC Toolkit is a DOS-based application written in Borland C++. Its routines, however, are transportable to other domains with a minimal amount of revision. It was a conscious decision to write the application based in DOS. This application would not have to share processor time with other applications, such as the ones running in Windows. This results in a higher bandwidth of operations since the processor is devoted to only one application. The trade off for using DOS is the limited number of colors available and the lack of 3-dimensional graphics rendering routines. Therefore, the MAGIC Toolkit comprises of a 2-dimensional visual display and a 3-dimensional haptic workspace. The haptic control loop update frequency for this program is approximately 1500 Hz. This is the performance when running on a 90 MHz Pentium processor. It will of course have a higher bandwidth with a faster processor.

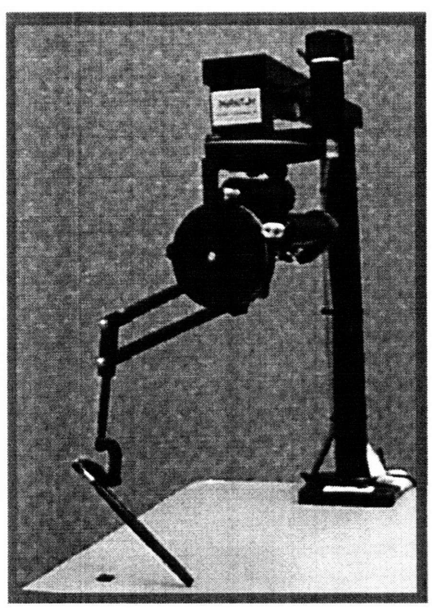


Figure 2-1: PHANToM Haptic Interface

2.3 Modes of Operation

The MAGIC Toolkit has several modes of operation. First, it allows the user to feel and explore the environment. Second, it allows the user to move the selected object in the scene by touching the selected object and pushing it around. Third, it allows the user to add objects to the scene and edit the features of the objects.

2.4 Coordinate System

The coordinate system of this application is centered in the middle of the haptic workspace. The x axis is on the horizontal plane starting at the center and pointing to the right. The y axis is on the horizontal plane starting at the center and pointing forward and away from the user. The z axis is on the vertical plane starting at the center and pointing up. Figure 2-2 shows a diagram of the coordinate system.

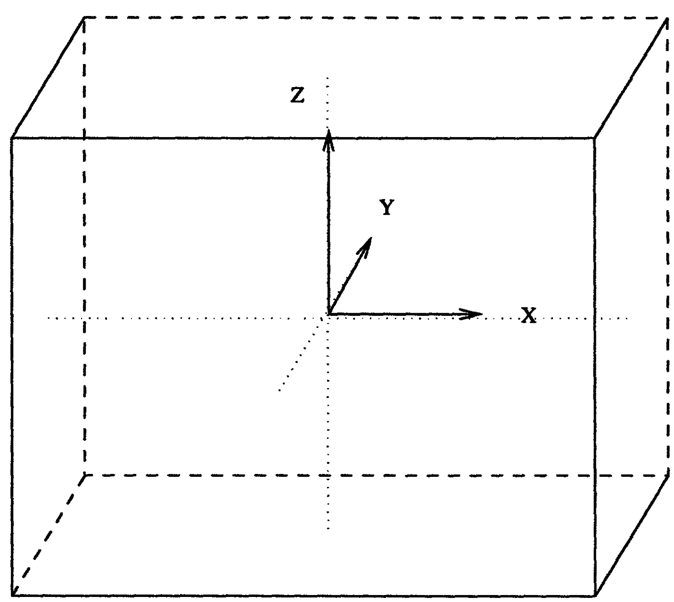


Figure 2-2: The Coordinate System

2.5 Object Primitives

Object primitives are pre-programmed objects that have visual and haptic characteristics that can be modified to create a virtual scene. The object primitives in the MAGIC Toolkit include a sphere, cylinder, cone, cube, and rectangular prism. When the user touches an object with the PHANToM, the user will feel a contact force appropriate for the object. The contact forces are calculated the simple linear spring law,

$$\vec{F} = -k\vec{x} \tag{2.1}$$

The force, F, is proportional to the amount of indentation, x. The indentation, x, is the amount of penetration into the object from the surface. The force is directed in the opposite direction of the indentation vector. The following is a description of how each of these primitives is constructed.

2.5.1 Sphere

The sphere is haptically and visually defined by a 3-dimensional centerpoint and a radius. It is one of the simpler objects to render. All the force vectors point radially outward from the centerpoint. Figure 2-3a shows the 3-dimensional sphere. Figure 2-3b shows a cross-section of the sphere with the force vector directions.

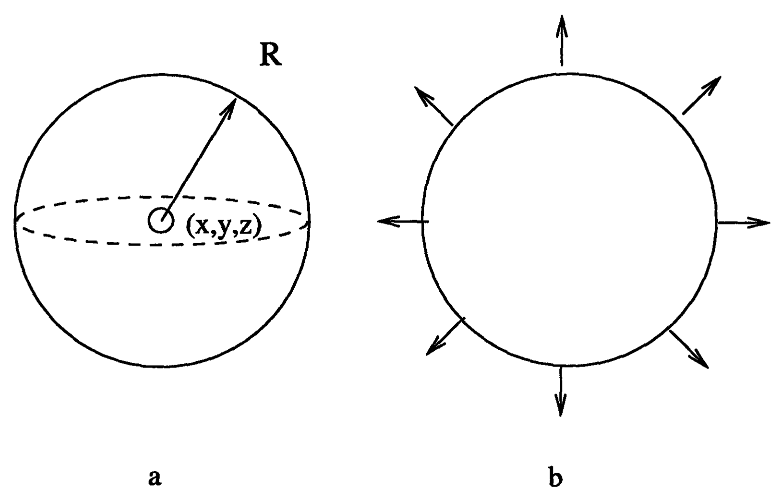
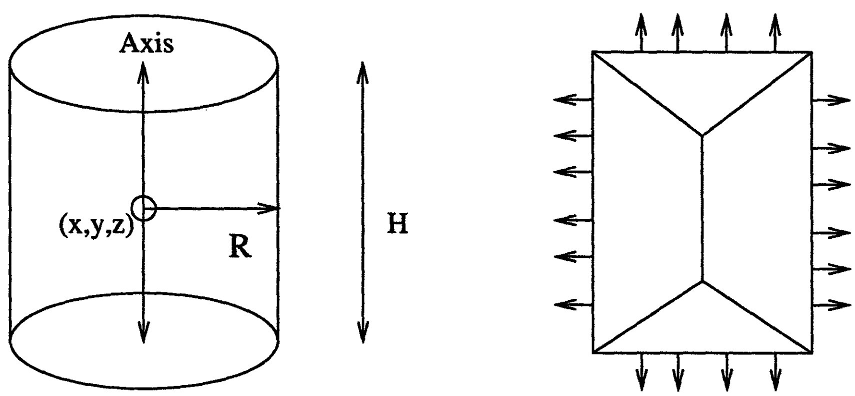


Figure 2-3: Sphere

2.5.2 Cylinder

The cylinder is defined by a 3-dimensional centerpoint, a length, a radius, and an axis of orientation. It is composed of three surfaces. The top and bottom surfaces are defined as planes with constraints at the circumference of the circle. When the user touches these surfaces, the contact force returned is normal to the surface. The third surface is the body of the cylinder. All the force vectors for the body of the cylinder point radially outward from the central axis. The central axis is the line through the centerpoint pointing in the same direction as the axis of orientation. Near the intersection of the body and the planar surface, the forces are defined by the location of the cursor. Of the two force vectors that may apply, the one of lessor magnitude is returned. Figure 2-4a shows the 3-dimensional cylinder with the key attributes. Figure 2-4b shows a cross-section of the cylinder with the force vector directions associated with each region.



a b

Figure 2-4: Cylinder

2.5.3 Cone

The cone is defined by a 3-dimensional centerpoint, height, and base radius. The centerpoint is located at the center of the base of the cone, as shown in Figure 2-5a.

The cone is composed of two surfaces, the body and the base. The force vectors for the body point radially outward from the central axis. The central axis is the line passing through the centerpoint and the vertex of the cone in the z-axis direction. Currently, the cone has only one orientation. The base of the cone is a planar surface constrained by the circumference of the circle defined by the base radius. The force vectors for the base are directed along normals to the base surface. The rendering method of the cone does

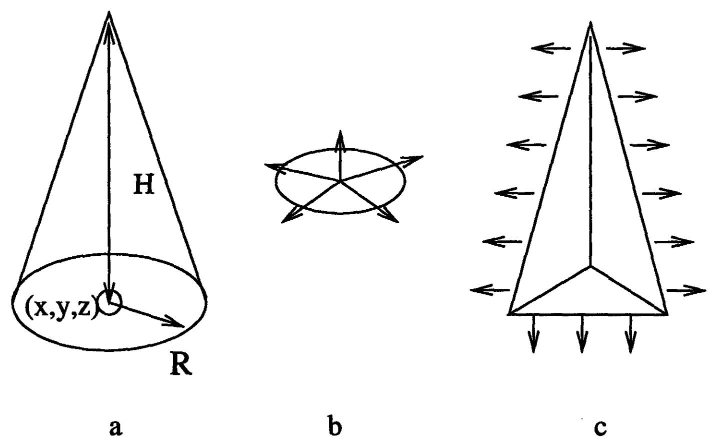


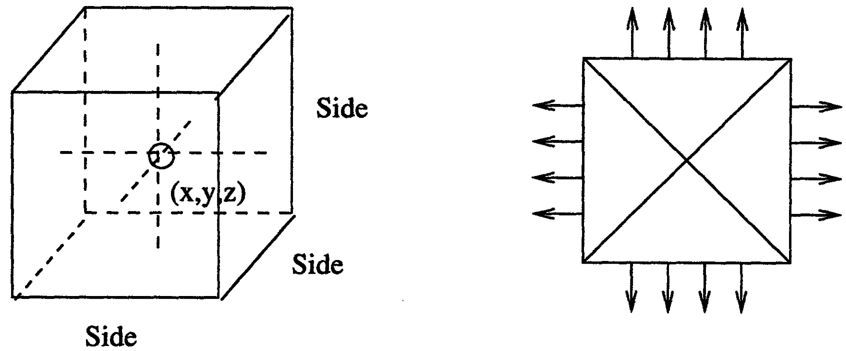
Figure 2-5: Cone

not depict a true cone since the force vectors returned for the body of the cone are not perpendicular to the surface. They are rather, perpendicular to the central axis. This is a simple rendering algorithm, requiring very few calculations, but still creates a cone that is haptically indistinguishable from one that has a force vector normal to all surfaces. One limitation of this rendering algorithm is the difficulty in feeling the vertex of the cone. Figure 2-5b shows the horizontal cross-section of the cone with the associated force vector directions.

Near the intersection of the conical and planar surfaces, the force vector with the lesser magnitude is returned. Figure 2-5c shows the vertical cross-section of the cone with the respective force vectors for each of the surfaces.

2.5.4 Cube

The cube is defined by a 3-dimensional centerpoint and the length of one side as shown in Figure 2-6a. It is composed of six perpendicular planar surfaces. The force fed back is based on the location of the cursor. A square cross-section is essentially divided into four triangular regions by drawing the diagonals as shown in Figure 2-6b. Each of the triangular regions has an associated force in a corresponding planar direction. If the cursor is within the region, the force vector is in the direction normal to the surface of the cube. Now, in the three dimensions, the cube is divided into six tetrahedral volumes. In each of the volumes, the force vector will always point in the direction normal to the outer surface.

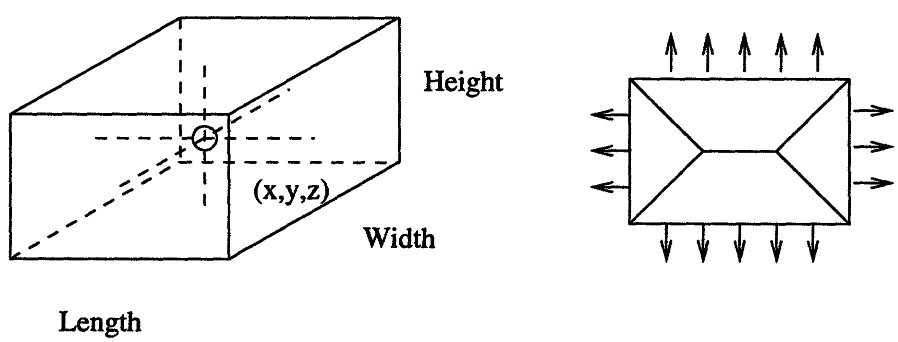


a b

Figure 2-6: Cube and Cross-sectional View with Force Vectors

2.5.5 Rectangular Prism

The rectangular prism is defined by a 3-dimensional centerpoint, length, width, and height as shown in Figure 2-7a. The prism is similar to the cube, differing only in the values for the length, width, and height. Figure 2-7b shows the cross-sectional view of the rectangular prism with the associated force vectors for each surface.



a b

Figure 2-7: Rectangular Prism

2.6 Functions

2.6.1 Location Variation

The X, Y, and Z centerpoint location of each object can be changed in increments of 0.1 inch using the menu bar.

2.6.2 Size Variation

The parameters available for changing the size of an object include length, width, height, and radius. The user can change the values of each of these parameters in increments of 0.1 inches. When the parameter is not applicable for the selected object, for example a radius for the cube, the value is not incremented.

2.6.3 Stiffness Variation

The stiffness of the object has an initial value of 0.1. It can be changed in increments of 0.01 and has a range of 0 to 0.2.

2.6.4 Color Variation

The colors available to chose from include: Black, Blue, Green, Cyan, Red, Magenta, Brown, Light Gray, Dark Gray, Light Blue, Light Green, Light Cyan, Light Red, Light Magenta, Yellow, and White. These are the 16 colors available for the DOS routines.

2.7 User Interface

Figure 2-9 shows the visual display when the MAGIC Toolkit program is running. There is a blue background, a cursor, two buttons indicating the feel and move mode of operation, two switches that allow for editing of the workspace, a button that will trigger the current scene to be saved into a file, and three information display boxes indicating the force output, the current cursor location, and the centerpoint of the selected object. All buttons and switches are haptically located on the vertical front wall of the haptic workspace. A touch to the region of the switch or button using the haptic interface device will trigger the respective action.

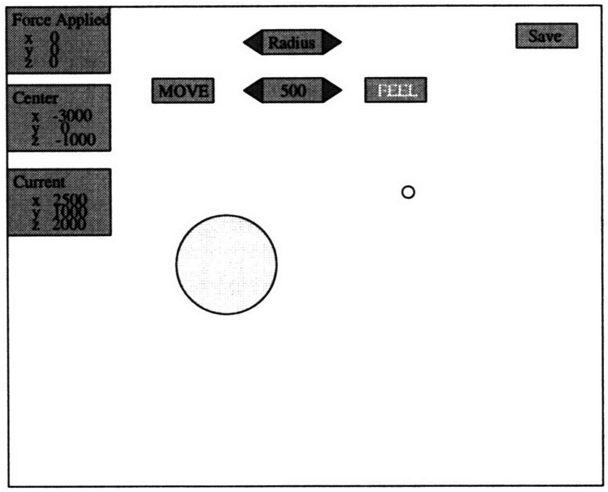


Figure 2-8: Visual Display of MAGIC Working Environment

2.7.1 Modes of Operation

There are two black buttons located symmetrically at the top, center region of the visual and haptic workspace. One is the FEEL button, located on the right. The other is the MOVE button, located on the left. The application is always in one mode or the other. The active mode is written in white, while the inactive mode is written in red. The FEEL and MOVE mode, as described earlier, allows the user to explore and manipulate the virtual environment, respectively.

2.7.2 Switches

There are two switches visually located at the center top of the screen one above the other. Each has two triangular, red incrementation arrows located on either side of the black label area. In the haptic space, the switches are located at the top center of the front wall. When the user touches one of the switches, a short auditory blip signals the activation of the switch. One switch toggles the parameters, the other switch toggles the values of the parameters. The parameters include: CENTER X, CENTER Y, CENTER Z, LENGTH, WIDTH, HEIGHT, RADIUS, ADD, SELECT, COLOR, and STIFFNESS. CENTER X is the x component of the centerpoint of the selected object. CENTER Y is the y component of the centerpoint of the selected object. CENTER Z is the z component of the centerpoint of the selected object. LENGTH, WIDTH, HEIGHT, and RADIUS are the size parameters of the selected object. If the parameter is not applicable, it has a value of zero. ADD is an editing feature that allows the user to add an object to the scene. Objects include a sphere, a cone, a cylinder, a cube, and a rectangular prism.

All objects have an initial centerpoint at (x, y, z) = (0, 0, 0) and a stiffness value of 0.1. The dimensions of the objects and locations are given in mils, (0.001 inches). The initial sphere has a radius of 500 mils and an original color of red. The initial cone has a radius of 500 mils, a height of 500 mils, and a color of green. There are three initial cylinders, one along each axis, that all have a radius of 500 mils, a height of 500 mils, and a color of green. The initial cube has a length of 500 mils, and a color of cyan. There are three initial rectangular prisms with an initial color of red, in which the dimension along one axis is longer than the dimensions in the other two. One has an initial length of 1000 mils, a width of 1000 mils, and a height of 500 mils. The other has an initial length of 5000 mils, a width of 1000 mils, and a height of 500 mils. The last has an initial length of 1000 mils, a width of 5000 mils, and a height of 500 mils.

When an object is selected, a white border outlines the shape.

2.7.3 Load/Save Options

When the program first starts, it prompts the user for the file he/she wishes to load. If there is such a file, it is loaded; if not, the user is given a fresh scene. Once the user has edited the file or created a new scene, there is a save button located at the top right corner of the front wall. The user is then prompted to enter the name of the file to save the information. Also, when the user enters "q" from the keyboard, the same prompt will appear before exiting the program.

The file that the information is saved to has the following format. It first saves the number of objects in the scene. It then saves the information about each object. The information saved is in the following order: object number, color, radius, length, width, height, x centerpoint location, y centerpoint location, z centerpoint location, x axis of orientation value, y axis of orientation value, z axis of orientation value, stiffness, and object type.

2.7.4 Information Display

On the left side of the screen, the x, y, and z components of the force applied, the present cursor position, and the selected object's center location are displayed.

2.8 Library Files

Associated with the MAGIC Toolkit program, is a set of library files that defines how each object and its features are associated. Once the virtual scene is saved as a *.mgc file, it can then be used in other applications. The library files allow the scene file to be loaded, drawn, and manipulated in various ways.

One of the library files defines the class in which the objects are organized and structured. Another file has many routines useful in manipulating the scene. The following describes the functions.

- load-scene: This function loads the scene by transferring the information in the file and assigning it to the objects. It also returns the number of objects in the scene.
- draw-scene: This function draws the objects in the scene for the specified point of view, either from the x, y, or z axis.
- erase-scene: The function visually draws the objects within the scene in the color blue, the background color. This in essence erases the scene.
- save-scene: This function saves the object characteristics in a specified file.
- scale-scene: This function scales the objects in two of three dimensions.
- change-color: This function changes the color of the specified objects to the desired color

2.9 Evaluation

Currently, the visuals are drawn as a 2-dimensional projection. It is at times difficult to locate an object in a 3-dimensional space when only given a 2-dimensional view. A method used to help locate the object has the user place the stylus along the same projectional space as the object. Visually the cursor would be touching or inside the object. The user then moves the stylus along the axis of projection until the object is found. In the future, the visuals could be presented as a 3-dimensional by using field sequential displays, such as Crystal Eyes, or a shaded representation of the scene to give the appearance of a three dimensional view. This set of complex graphics will require more processing power due to the inherent nature of 3-dimensional graphics to be run in real time. It is likely that a separate processor or computer devoted to visual rendering will be needed, though advances in computer technology may develop a processor that can handle both the 3-dimensional graphics and 3-dimensional haptics rendering. Another avenue is to develop efficient graphics rendering algorithms that can use DOS to create realistic 3-dimensional images. Running on a single system reduces the complexity of the overall structure. It also reduces the cost of the operating system.

A framework developed to characterize an object's visual and haptic features is easily expandable to include other features such as texture, mass, density, viscosity, and other material properties. An ideal Magic Toolkit would include dynamic interactions between the objects and the user. In other words, it would be able to create a pin joint, a ball socket, and a sliding joint. This would allow for the simulation of virtual mechanisms.

An application like the MAGIC Toolkit is very useful in creating virtual environments. It provides a virtual workspace to design, create, edit, and explore. There are no material costs in designing in this medium. Complex geometries can be modeled easily. A complex object can be created using simple object primitives and used in later applications. This versatile Toolkit can create training environments for various tasks, create standardized environments to test and record reactions and evaluate a patient's progress, model structures and products to test for viability, robustness, and feasibility, and create imaginative environments to just have fun in, or develop motor coordination skills.

In the rest of this thesis, the use of the MAGIC Toolkit to create virtual mazes to test human performance in various visual haptic paradigms is described. These experiments are done in an effort to understand how different visual and haptic cues will alter human performance and to find what type of visual-haptic interaction humans prefer.

Chapter 3

Visual-Haptic Interactions

3.1 Motivation

Virtual Environments is a relatively new field. Very little is known of how best to interact in this environment. Because this field is still in its infancy, there are some basic questions to be answered and terminology that needs to be defined. Some of the questions are:

1. What are the different types of haptic-visual interactions that are possible ? In terms of relative display sizes? In terms of motion? In terms of force? In terms of background and cursor relationships?

2. What type of relationship SHOULD the haptic and visual workspace have?

3. In what situations would it be beneficial to have one type of interaction over another?

4. What are the advantages and disadvantages of each of the different paradigms?

5. How can a particular implementation of the haptic-visual workspace improve the sense of immersion?

6. Which type of haptic-visual workspace is most "comfortable" and "natural" for the user?

7. What types of skills and motions are required by each of the different paradigms?

8. How large should the visuals or haptics be? How large does the visual or haptic workspace need to be?

9. How feasible is it to emulate large-scale haptic workspace in a much smaller haptic workspace?

10. Can a small haptic workspace be mapped to a perceptually large workspace using visual or force cues?

This chapter on Visual-Haptic Interactions will define some of the modes of interaction. To find how humans act and react to these paradigms and variations, perceptual experiments need to be performed. The end goal is to find what type of interaction paradigm would be comfortable and easy to use, and which is ideal for certain tasks.

3.2 Visual and Haptic Size Variations

Since the physical workspace of the PHANToM or of any haptic interface is limited, it would be interesting to see if increasing the size of the visual display would cause the user to perceive a larger workspace. It would also be interesting to find the effects of scaling one modality versus the other. Enlarging the visual display is analogous to looking at the workspace through a magnifying lens.

A set of experiments was designed using two visual workspaces of different sizes and two similar haptic workspaces of different sizes. Pairing each visual workspace with haptic workspace results in the matrix shown in Table 3.1.

Table 3.1: Visual-Haptic Size Variations

Haptic Size	Visual Large	Size Small
Large	Variation 1	Variation 2
Small	Variation 3	Variation 4

Given this set of variations it would be interesting to see how subjects perform if they are told to minimize time versus if they are told to minimize error, where an error is defined as any contact with the walls of the maze. It would also be interesting to see the variations in their performance given different combinations of sensory feedback. A subject could be presented with only visual feedback, with only haptic feedback, or with both haptic and visual feedback. One would suspect the subjects would perform best if encouraged to use as many senses as available. However, whether they would perform better with just visual feedback or with just haptic feedback is unclear. One hypothesis is that performance would be better with just haptic feedback because the haptics is an interactive modality, whereas vision is purely sensory.

Also, the performance in one variation versus another for the different objectives is also unclear. One would suspect that larger haptics would have fewer errors since there is physically more room to move in, and that larger haptics would require more time to complete because the path would be longer. One might also suspect that large visuals would have a better performance than small visuals. Conducting this set of experiments would give conclusive results as to the user performance and preference in these variations and tasks.

3.3 Visual Scaling Effects on Training

One might also wonder about the effects of training on a large visual size versus training on a small visual size. If there are a number of visual displays differing only in size, and a subject is presented with a small visual workspace for training, followed by presentations with the other visual sizes, this is considered an increase in the visual scaling. Similarly, if the subject is first presented with the largest visual workspace, this is considered a decrease in visual scale. In general, visual scaling is defined as increasing or decreasing the visual display size throughout a given task.

One would suspect that larger visuals would result in a better performance. However, would performance always improve with an increase in visual size? Is there a limit in which performance would level off or even decay? Conducting an experiment with this theme would require several visual size displays and a single haptic size display. One might also wonder about the performance in these variations if trained on a large visual display versus a small visual display. Training on a small visual display would give the impression of scaling up whereas training on a large visual display would give the impression of scaling down. Results of this experiment would tell if there is a limit to visual dominance effect and if there is a benefit in training on a certain size display. Table 3-2 lists a set of variations in which the haptic size remains constant and the visual size increases.

Table 3.2: Visual Scaling Variations

	Visual Size	Haptic Size
Variation 5	Small	Small
Variation 6	Medium	Small
Variation 7	Large	Small
Variation 8	Ex-large	Small

3.4 Cursor Paradigms

There are many variations in which a user can interact with the VE using a haptic device and see the results of that interaction. The cursor and the scene are two parameters that can be varied in both the visual and haptic domains. The cursor can be stationary or it can be mobile. The scene can be mobile or stationary. Two broad categories of this interaction is in terms of position control and force control. For position control, the haptic cursor is moving. For force control, the haptic cursor is stationary. The display of these interactions can be coupled with a moving scene or a stationary scene in both the visual and haptic environments. A more detailed description of the cursor paradigms will explained in the next section. Conducting an experiment with the cursor paradigms will reveal human performance in these different environments. This will give insight to human reaction in these various virtual environments, so that in the future, should a certain task require a similar human control of the virtual environment, there will be an understanding of performance and preference. Table 3-3 shows the different characteristics of each of the cursor control paradigms.

Table 3.3: Cursor Paradigms

Analogy	"mouse"	"magnifying lens"	"tele-video"	"RC car "
Visual Cursor	moving	static	static	moving
Visual Environment	static	moving	moving	static
Haptic Cursor	moving	moving	static	static
Haptic Environment	static	static	moving	moving
Control Type	Position Control	Position Control	Force Control	Force Control

3.4.1 Position Control

In position control, the motion initiated through a haptic device results in a similar movement in the visual workspace. One familiar type of position control is that of using the computer mouse. When the mouse moves by a certain amount in physical space, a cursor moves by a proportional amount in the visual space. This "mouse" type of position control is characterized by a stationary visual environment and a stationary haptic environment while the visual and haptic cursors are moving synchronously.

An alternative method of position control is analogous to exploring an environment with a "magnifying lens". Imagine a person holding a magnifying lens in one hand and move it freely to view locations of interest. The magnifying lens itself is the haptic cursor moving in a static haptic environment. As the person looks through the lens, the visual moves in a direction opposite to the motion of the lens, while the visual cursor at the center of the lens is stationary relative to the lens frame. The person sees a visual environment moving to the left when the magnifying lens is moved to the right. The "magnifying lens" type of position control is characterized by a stationary visual cursor, a moving haptic cursor, a stationary haptic environment, and a moving visual environment.

3.4.2 Force Control

In force control, the motion initiated by the user results in a force felt in the haptic environment, and the force applied by the user governs the cursor location and motion of a visual display. The force applied results in a motion proportional to the velocity of the element in the visual space. For example, a video game joystick moves a character in the direction of applied force.

There are two types of force control. The first, which is called "tele-video", has a stationary visual and haptic cursor, and a moving visual and haptic environment. This is analogous to a video camera that hangs over the field of some sports stadiums. This is used to capture a close-up view of the athletes during the game. The field of view of the camera is fairly narrow, but the camera can be moved to a desired location. An editor in a production room controls this video camera. The editor can see the athletes on the field via a monitor which displays the field of view of the video camera. When the editor tries to visually follow an athlete running across the field, he/she applies a force to a joystick in the desired direction. The athlete appears at the center of the screen and the visual environment moves in a direction opposite to that of the applied force. In this analogy, the center of the monitor is the stationary visual cursor and when the editor applies a force to the controller, he/she operates stationary haptic cursor.

The second, which is analogous to a radio controlled toy car, has a stationary haptic cursor, a moving visual cursor, a stationary visual environment, and a moving haptic environment. Imagine a person maneuvering a radio controlled car around an obstacle course. The person is standing at a distance watching the toy car move as he/she applies force to the controller in the desired direction. The car is the moving visual cursor. As the person watches, he/she sees a stationary visual environment. The joystick in the radio control box is the stationary haptic cursor. The force applied to the controller results in a motion of the car. This paradigm is called "RC car" for short.

Chapter 4

Experiments

The task of completing a maze was chosen for its simplicity and complexity. The maze was designed to have a single path. Multiple paths were not needed since the subjects were not being tested on their cognitive skills. The path of the maze had various sizes to change the complexity level. It also had many turns and obstacles in the path.

4.1 Experimental Procedure

All the subjects in these experiments were right handed and between 20 to 28 years of age. At the start of each session, each subject was asked to read and sign a consent form for participating in the experiment (see Appendix A). A short demonstration of how to use the PHANToM preceded the start of the experiment. The instructions for the experiment were presented as a prompt on the monitor. Once the instructions had been read, the subject's understanding of the procedure was verified.

At the start of each trial, each subject was asked to center the stylus of the PHANToM. Two cursors representing the subject's 3 dimensional position was displayed. One cursor's position was a view of the x-z plane. The other cursor's position was a view of the y-z plane. When the subject centered both cursors in the middle of a circle on the screen, the stylus would be centered in the haptic workspace, thus ensuring the same starting position for each trial. This also guaranteed that the subject did not start the maze when the cursor was within an object which would result in an unexpected force when the maze was displayed haptically.

Once the subject completed the maze, he/she was asked to rate the difficulty of completing the maze on a scale of 1 to 5.

- 1 = very hard
- 2 = hard
- 3 = medium difficulty
- 4 = easy
- 5 = very easy

At the end of the session, each subject was asked to fill out a survey about the strategy used in completing the maze, the differences perceived among the mazes presented, and their preference for one maze over another.

4.2 Experimental Design

4.2.1 Apparatus

These experiments were conducted with T-Model version 1.0 high resolution PHANToM haptic interface and a 90 MHz Pentium Processor running in DOS. The subject sat in a chair approximately 30 inches away from a NEC MultiSync 5FGe 17 inch, 0.28 pitch monitor. Since all the subjects were right-handed, the PHANToM was located to the right of the subject with an arm rest to support the arm during the experiment. The keyboard was located in front of the subject and used to start and rate the trials of the maze. The experimental apparatus is shown in Figure 4-1.

4.2.2 Maze

The maze was created using the MAGIC Toolkit. It was composed of rectangular prisms and cylinders such that when one looks at the projection in the x-z plane the maze can be seen. It had two additional objects in the scene acting as a starting block and finishing block that triggered the timer and the log of locations and errors. The starting block was located at the center of the workspace, and the finishing block was located in the lower half of the workspace.

The maze started with the cursor at the center of the visual and haptic workspace. Figure 4-2 shows the x-z projection of the maze. The user had to move slightly to the left

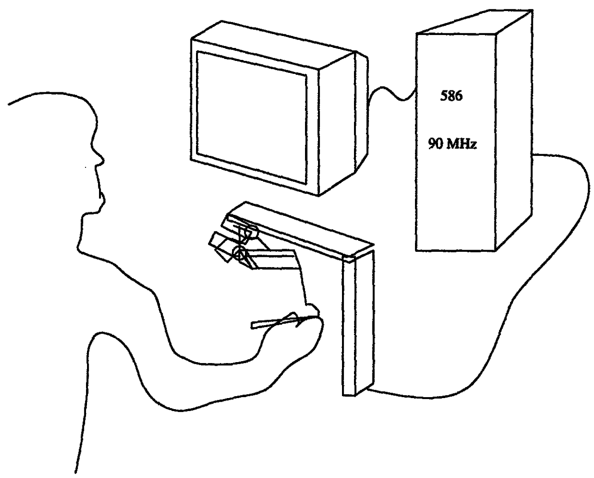


Figure 4-1: Experimental Apparatus

to contact the green starting block so as to trigger the timer. Touching the starting block resulted in a change of color from green to light green, thus giving the subject a visual cue that the trial began. Once the subject released the starting block, the timer started. The recording of the 3-dimensional location of the cursor started as soon as the subject was presented with the maze and ended when the subject touched the finishing block.

The subject followed the path of the maze to a black finishing block. Once the subject touched the finishing block, the timer and log stopped and the subject was asked to rate the ease of completing the maze. Then the next trial began.

4.3 Visual-Haptic Size Variations

Experiments 1, 2, 3, and 4 used the four visual-haptic size variations listed in Table 4.1. There were two sizes, small and large, for the visual and haptic workspace. The small size had dimension of 4"x2.25". The large size was 1.5 times larger with dimensions of 6"x3.25". A scaling factor of 1.5 was chosen due to the limits of the haptic workspace. Variation 1 had a large visual and a large haptic workspace. Variation 2 had a large haptic workspace and a small visual workspace. Variation 3 had a small haptic workspace and large visual workspace. Variation 4 had a small visual and a small haptic workspace. Figure 4-3 shows a graphical representation of the four variations.

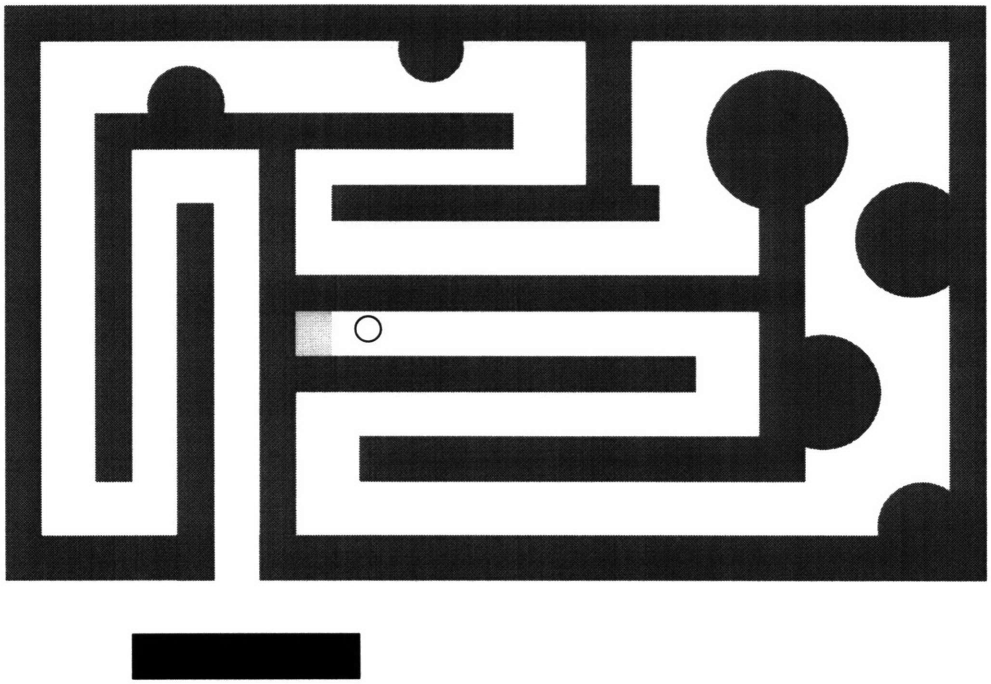


Figure 4-2: A Typical Maze

Table 4.1: Visual-Haptic Size Variations

Haptic Size	Visual Size	
	Large	Small
Large	Variation 1	Variation 2
Small	Variation 3	Variation 4

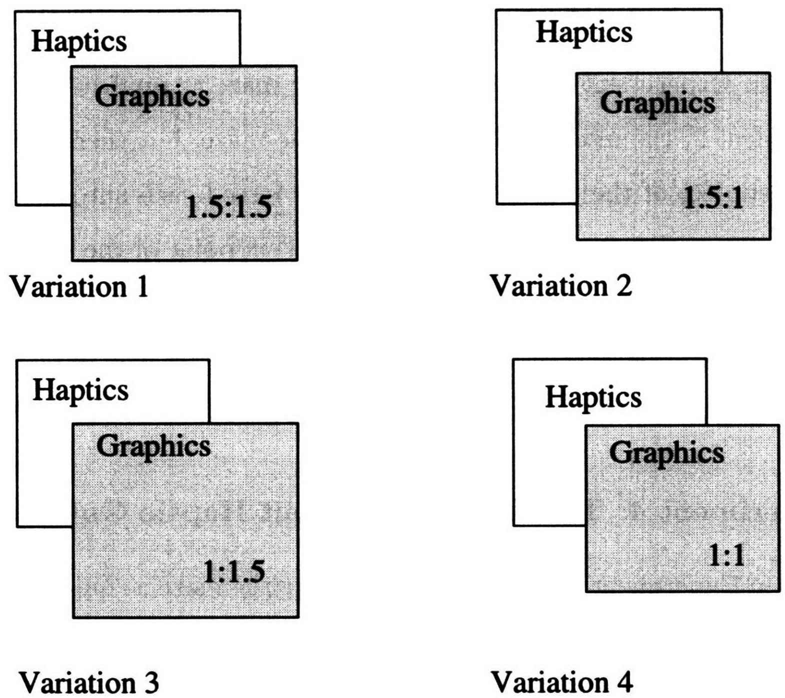


Figure 4-3: Variations of Two Visual Sizes and Two Haptic Sizes

4.3.1 Experiment 1: Tests Accuracy

In Experiment 1, the subjects were told to complete each of the mazes while minimizing contact with any wall of the maze. The session consisted of 62 trials, starting with 10 training trials of Variation 1, followed by 52 randomly distributed trials of the four variations. The last 28 of the 62 trials had ratings for ease of use. Seven subjects were tested in this experiment.

4.3.2 Experiment 2: Tests Speed, With Visual and Haptic Guidance

The objective in Experiment 2 was to complete the maze as quickly as possible by seeing the visual position of the cursor and feeling the haptic cursor against the surface of the maze wall.

The session consisted of 45 trials. There were five training trials on Variation 1 and 40 random trials of the four variations. Since the five subjects in this experiment were also subjects in Experiment 1, only a small number of training trials were needed to refresh their memory on how to use the apparatus.

4.3.3 Experiment 3: Tests Speed, Without Visual Cursor Guidance

The objective in Experiment 3 was to complete the maze as quickly as possible. However, unlike Experiment 2, the monitor displayed only the maze, but there was no visual cursor to inform the subject of the current location. This forced each subject to rely exclusively on his/her haptic sense to assess the location of the endpoint of the stylus.

This session consisted of 45 trials. There were five training trials on Variation 1 and 40 randomly distributed trials of the four variations. The same five subjects who performed in Experiment 1 and 2 also participated in this experiment.

4.3.4 Experiment 4: Tests Speed, Without Haptic Guidance

The objective in Experiment 4 was again to complete the maze as quickly as possible. However, in this experiment, there was no haptic feedback when the subject had the endpoint of the stylus in the physical space of the walls of the maze. This forced each subject to rely exclusively on his/her visual sense.

This session consisted of 45 trials. There were five training trials on variation 1 and 40 randomly distributed trials of the four variations. The five subjects who participated in this experiment also performed in Experiment 1, 2, and 3.

4.4 Visual Scaling Effects on Training

Experiments 5 and 6 used the visual-haptic variations listed in Table 4-2. There were four visual sizes and one haptic size. Size "Small" had a visual display of 4"x2.25". Size "Medium" was 1.5 times larger than "Small". Size "Large" was 2 times larger than "Small". Size "Ex-large" was 2.5 times larger than "Small". The haptic size presented was the same as "Small". Variation 5 had "Small" visual and haptic workspaces. Variation 6 had a "Medium" visual workspace and a "Small" haptic workspace. Variation 7 had a "Large" visual workspace and a "Small" haptic workspace. Variation 8 had an "Ex-large" visual workspace and a "Small" haptic workspace. Figure 4-4 shows a graphical representation of the four variations used in the visual scaling experiments.

These experiments were designed to investigate the performance of users when presented with one haptic size and several visual sizes. It studied the effects of training time on a small visual size and the effects of training on an extremely large visual size while the haptic

Table 4.2: Visual Scaling Variations

	Visual-Haptic Ratio	Name
Variation 5	1:1	Small
Variation 6	1.5:1	Medium
Variation 7	2:1	Large
Variation 8	2.5:1	Ex-large

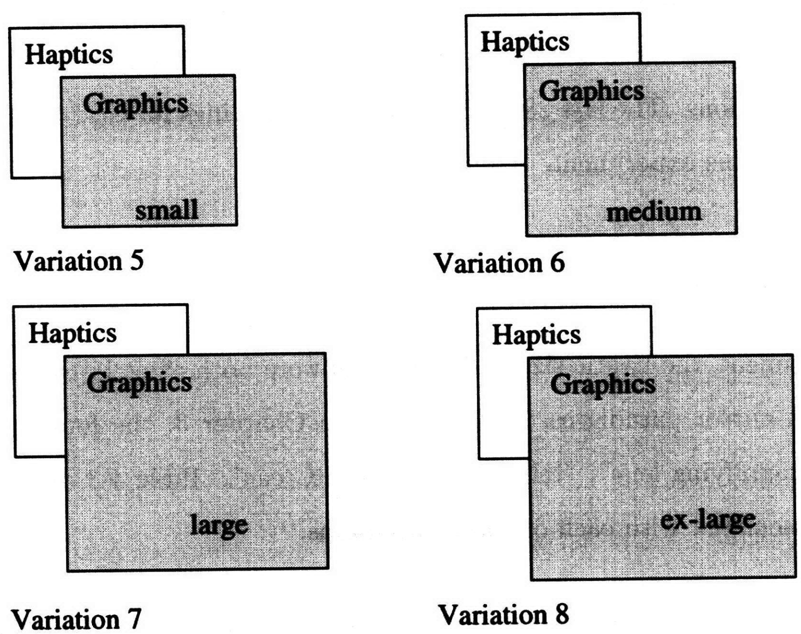


Figure 4-4: Variations of Four Visual Sizes and One Haptic Size

size remained the same.

4.4.1 Experiment 5: Increasing Visual Scale (Training on a Small Visual Size)

The subjects were asked to complete each of the mazes while minimizing contact with any wall of the maze. The session consisted of 62 trials. Ten were training trials of Variation 5. The subjects were trained on a "Small" visual workspace and a "Small" haptic workspace then presented with 52 trials with a random distribution of the four variations. The last 28 of the 62 trials had ratings for ease of use. There were seven subjects.

4.4.2 Experiment 6: Decreasing Visual Scale (Training on a Ex-Large Visual Size)

The subjects were asked to complete each of the mazes while minimizing contact with any of the walls of the maze. The session consisted of 62 trials. In this experiment, the 10 training trials were of Variation 8. The subjects were trained on the "Ex-large" visual workspace and the "Small" haptic workspace. Training on a large visual display conveyed the impression that everything else was scaled down. The remaining 52 trials were a random distribution of the four variations. The last 28 of the 62 trials had ratings for ease of use. Seven subjects participated in this experiment.

4.5 Cursor Paradigms

In this experiment, the haptic size and the visual were both 4"x2.25". There were however, four different cursor paradigms. As described in Chapter 3, the four paradigms include: "mouse", "magnifying lens", "tele-video", and "RC car". Table 4-3 describes the different attributes associated with each of these paradigms.

4.5.1 Experiment 7: Position and Force Control Cursor Paradigms

The objective of this experiment was to complete the maze a quickly as possible without passing though the walls of the maze. Due to the limits of the motor torque output, the walls of the maze did not feel infinitely stiff. It was therefore possible to pass through the walls when too much force was applied, such trials were rejected for the final data analysis.

Table 4.3: Cursor Paradigms

Analogy	"mouse"	"magnifying lens"	"tele-video"	"RC car"
Paradigm	1	2	3	4
Visual Cursor	moving	static	static	moving
Visual Environment	static	moving	moving	static
Haptic Cursor	moving	moving	static	static
Haptic Environment	static	static	moving	moving
Control Type	Position Control	Position Control	Force Control	Force Control

There were seven subjects for this experiment. There were 72 trials in this session. This included 3 of each of the four paradigms for training for a total of 12 training trials, 48 randomly distributed trials of the four paradigms, and 12 randomly distributed trials of the four paradigms with a new maze. The new maze was constructed using the same number of objects with a slightly different arrangement. The size and difficulty of the two mazes were approximately the same. Figure 4-5 shows the x-z display of the new maze.

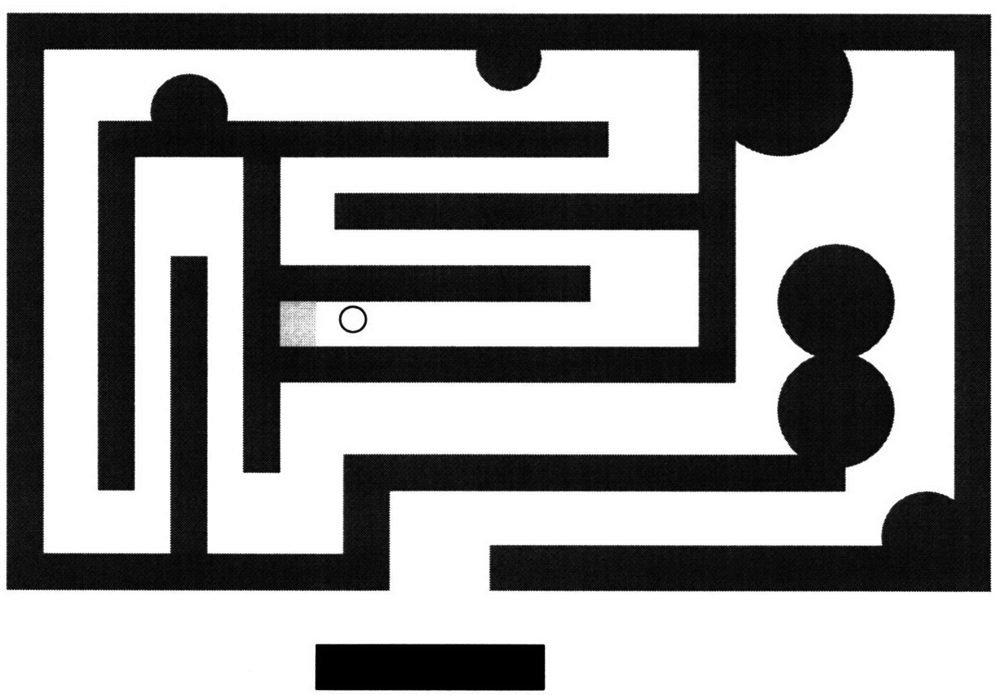


Figure 4-5: New Maze for Experiment 7

Chapter 5

Results

5.1 Performance Measures

5.1.1 Time Performance

The time at which a subject started the maze by touching the starting block at the time the subject touched the finishing block was recorded. The mean time required to complete the mazes for each of the paradigms or variations was compared.

5.1.2 Error Performance

There were two error measures, wall contact errors and wall crossing errors. For experiments in which the subjects were told not to touch the surface of the maze, any contact was counted as a wall contact error. This error count number was based on the number of cycles of the servoloop in which the subject was in contact with the maze wall. This was basically a sum of the time in which the subject contacted the wall. The servoloop ran at approximately 500 Hz.

In all the experiments, each time a subject used too much force and passed completely through a wall of the maze, it was counted as a wall crossing error. The location and time was recorded for each subject's session. There was a viewing program for each of the experiments to see the visual display of the subject's path through the maze. Using this program, a manual count of any passage through the walls of the maze could be determined.

5.1.3 Preference Rating

For each of the preference rated trials, subjects were asked to rate the ease of completing the trial on a scale of 1 to 5. The paradigm or variation associated with that trial was given points equal to the rating. All the points were then added up for each of the variations or paradigms. The one with the most points was ranked the easiest and the one with the least amount of points was ranked the hardest.

5.1.4 Performance Ranking

The performance ranking gave the order of best performance to worst performance by variation or paradigm number. For Example, if variation 3 had the best time performance, followed by variations 4, 1, and 2, the ranking would be 3, 4, 1, 2. For time performance, the least amount of time required was considered the best and the most amount of time required was considered the worst. For error performance, the least amount of error was considered the best and the most amount of error was considered the worst. For preference rating, the highest point value was considered the best and the lowest point value was considered the worst.

5.2 Methods of Analysis

5.2.1 Statistical

The mean, the standard error of the mean, and the median of the results were calculated for each of the variations of the experiments. In the experiments in which the subjects were asked to minimize error, subjects were able to complete trials without touching the walls of the maze. The number of trials in which the subjects had no errors were added for each variation in the accuracy experiments.

5.2.2 Boxplot

A boxplot as in Figure 5-1, shows the important statistical characteristics about a group of data. The box is centered at the median value and shows the upper quartile and lower quartile of the data. The notch represents a robust estimate of the uncertainty about the median for a boxplot to boxplot comparison. Whiskers are lines extending from each end of the box to show the extent of the data. The whiskers are a function of the interquartile range. The interquartile range is a robust estimate of the spread of the data since changes in the upper and lower 25% do not affect it. It is calculated by subtracting the 25th percentile from the 75th percentile and multiplying by 1.5.

5.3 Visual-Haptic Size Variations

Table 5.1 shows the matching of two visual sizes to two haptic sizes for the different variations used in Experiments 1, 2, 3, and 4. This set of experiments tested the significance of changing both the visual and haptic size parameters.

Table 5.1: Visual-Haptic Size Variation

Haptic Size	Visual Large	Size Small
Large	Variation 1	Variation 2
Small	Variation 3	Variation 4

5.3.1 Experiment 1: Tests Accuracy

In this experiment, the subjects were told to complete the maze as accurately as possible. They were asked to minimize contact with the walls of the maze as they followed the path from the starting block to the finishing block.

Table 5-2 shows the mean time results for the seven subjects of Experiment 1. Subject 5 required much more time to complete the maze than the rest of the subjects. A boxplot of the time results for all seven subjects, displayed in Appendix B, shows that most of the data for subject 5 was outside the range of data. Another set of statistics were calculated without the data from subject 5. The boxplot of this is shown in Figure 5-1. The trends were the same for either case, but the standard deviation was less for the 6 subjects. The following discussion is based on the data from 6 subjects.

Variation 3, with small haptics and large graphics, was completed in the least amount of time for six out of the seven subjects. The average time required to complete the maze with this variation was 15.0 $\pm$ 0.5 seconds. Variation 4, with small haptics and small graphics, was the second fastest in overall time performance with a mean time of 15.9 $\pm$ 0.5 seconds.

Table 5.2: Mean Time Performance for Experiment 1: Accuracy

	Var 1 (sec)	Var 2 (sec)	Var 3 (sec)	Var 4 (sec)	ranking
Subject 1	17.1	17.5	13.9	14.7	3,4,1,2
Subject 2	17.9	19	16.1	16.3	3,4,1,2
Subject 3	23.5	24.7	21.4	20.9	4,3,1,2
Subject 4	15.1	15.6	13.5	13.8	3,4,1,2
Subject 5 *	46.2	50.7	37.5	41	3,4,1,2
Subject 6	11.1	12.2	8.6	9.2	3,4,1,2
Subject 7	19.8	22.9	16.8	20.4	3,1,4,2
Statistics with 7 Subjects					
Average	21.5 ± 1.3	23.2 ± 1.5	18.3 ± 0.9	19.5 ± 1.1	3,4,1,2
Median	17.4	19.7	15.9	16.3	3,4,1,2
Statistics with Subjects 1,2,3,4,6,7					
Average (6)	17.4 ± 0.5	18.7 ± 0.6	15.0 ± 0.5	15.9 ± 0.5	3,4,1,2
Median (6)	16.8	19.0	14.6	15.9	3,4,1,2

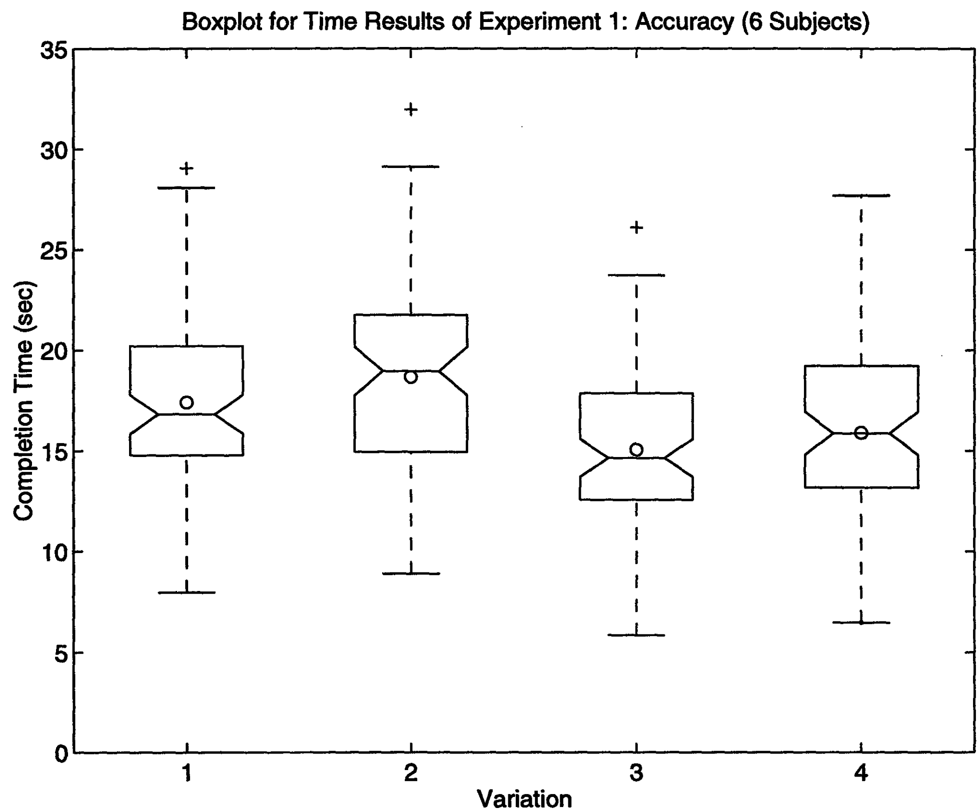


Figure 5-1: Boxplot of Time Results for Experiment 1: Accuracy. Variation 1: mean = 17.4 ± 0.5, median = 16.8. Variation 2: mean = 18.7 ± 0.6, median = 19.0. Variation 3: mean = 15.0 ± 0.5, median = 14.6. Variation 4: mean = 15.9 ± 0.5, median = 15.9. (sec)

Both of these variations had small haptics and required 12% less time to complete than the variations with large haptics. An explanation is that since the physical path to complete the smaller haptic maze was shorter, it required less time than the one with a longer path. The two variations with large haptics required the most amount of time to complete. Variation 1, with large graphics and large haptics, was completed faster than Variation 2, with small graphics and large haptic. Variation 1 required 17.4 ± 0.5 seconds to complete on average. Variation 2 required 18.7 ± 0.6 seconds to complete on average. These results showed that subjects performed faster when they were given small haptics than when they were given large haptics. The results also showed that if subjects were presented with single haptic size two visual sizes, performance was better with the large visual size than with the small visual size. The median time results were consistent with the mean time results. The median times required were 14.6, 15.9, 16.8, and 19.0 seconds for Variations 3, 4, 1, and 2 respectively.

Table 5-3 lists the mean error results for the seven subjects of Experiment 1. The following discussion is based on the analysis of the data from six subjects. Overall, the error count differences among the four variations were much smaller than the completion times. Relative to the high standard error of the mean in the error count, the differences in the mean values were negligible. Variation 1, with large haptics and large graphics, had the lowest error count, 451 ± 55. Subjects had more space visually and haptically to move, therefore, it was reasonable to see such a result. Variation 4, with small graphics and small haptics, also had a low error count, 465 ± 59. One explanation for this might be that small graphics instilled a sense of caution in the subjects resulting in a smaller error count. Both of these variations had a relatively low error count and had a one to one visual to haptic ratio. A high correlation between the visual and haptic workspace resulted in a low error count.

Variations 2 and 3, both of which had a skewed size correlation between the visual and haptic workspace, had high error counts. The small graphics of Variation 2 made subjects cautious, while the large haptics gave subjects more space to move, resulting in relatively fewer errors, 498 ± 58. Variation 3, with small haptic and large graphics, had the highest error count, 543 ± 61. This variation had large graphics which led the subjects to relax their caution in not touching the walls resulting in larger errors. Variation 3, which also had small haptics, required a high degree of motor control to maneuver in a small haptic

Table 5.3: Mean Error Counts for Experiment 1: Accuracy

	Var 1	Var 2	Var 3	Var 4	ranking
Subject 1	627	644	708	603	4,1,2,3
Subject 2	160	184	198	113	4,1,2,3
Subject 3	51	88	105	85	1,4,2,3
Subject 4	309	384	542	424	1,2,4,3
Subject 5 *	13	130	30	103	1,3,4,2
Subject 6	1292	1376	1409	1209	4,1,2,3
Subject 7	268	311	301	360	1,3,2,4
Statistics with 7 Subjects					
Average	389 ± 50	445 ± 54	470 ± 56	414 ± 52	1,4,2,3
Median	209	227	302	230	1,2,4,3
no error trials	18	11	17	14	1,3,4,2
Statistics with Subjects 1,2,3,4,6,7					
Average(6)	451 ± 55	498 ± 58	543 ± 61	465 ± 59	1,4,2,3
Median (6)	280	295	365	312	1,2,4,3
no error trials	8	3	8	8	(1,3,4), 2

space.

The median errors showed a slightly different trend with error counts at 280, 295, 312, and 356 for Variations 1, 2, 4, and 3 respectively. There was a number of trials in which the subjects made no errors. For Variations 1, 3, 4, and 2, there were 8, 8, 8, and 3 trials in which the subjects had no errors when completing the maze. Figure 5-2 shows the boxplot of the error results for Experiment 1.

There were no wall crossing errors any of the variations, since the subjects were told to minimize contact with the walls.

Table 5-4 shows the preference rankings of the variations for the seven subjects in Experiment 1. A high resultant score was equivalent to a strong perception of ease. According to the rankings, Variation 3, with small haptics and large graphics, was perceived to be the easiest to complete. Several subjects also equally rated Variation 1 and 3, both of which had large graphics. This implied that regardless of the size of the haptic workspace, so long as the visual presentation of that workspace was large, the user felt more at ease. Many subjects rated Variations 2 and 4 as equally hard to complete. These variations both had small graphics. Once again, the effects of visual presentation dominated performance. Variation 1 was ranked second easiest, followed by Variation 4. Variation 2 with large haptics

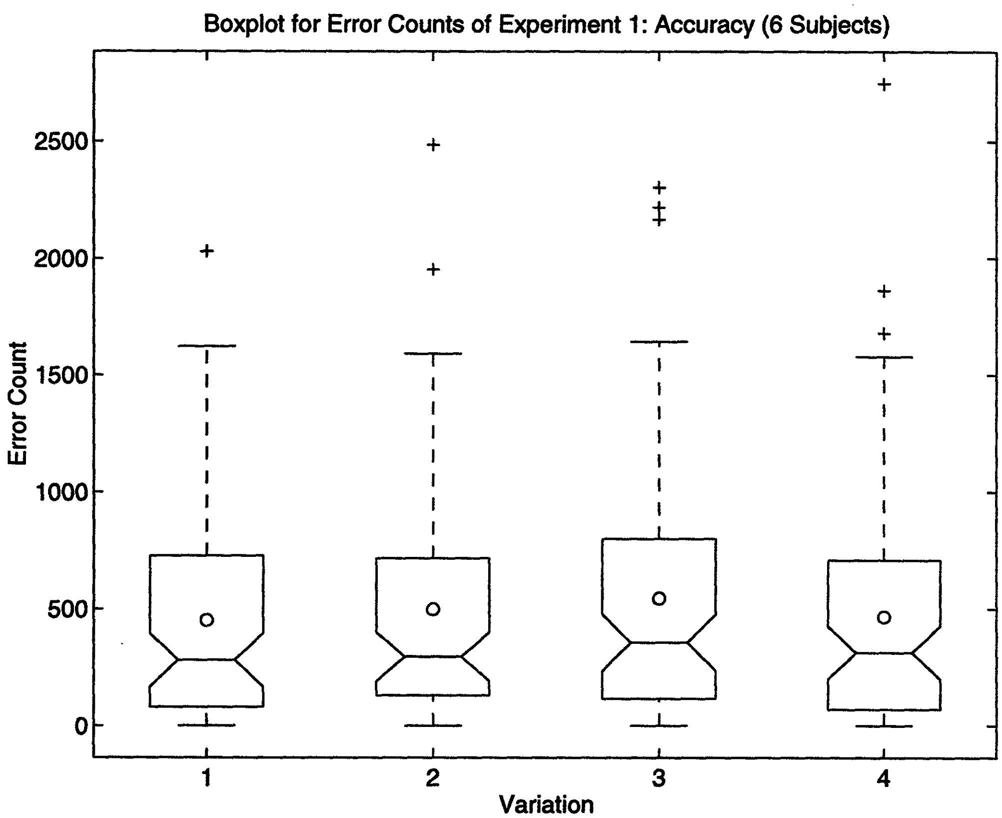


Figure 5-2: Boxplot of Error Results for Experiment 1: Accuracy. Variation 1: mean = 451 ± 55, median = 280. Variation 2: mean = 498 ± 58, median = 295. Variation 3: mean = 543 ± 61, median = 365. Variation 4: mean = 465 ± 59, median = 312. (counts)

and small graphics was rated the hardest to complete.

Table 5.4: Preference Rankings for Experiment 1: Accuracy

	Sub 1	Sub 2	Sub 3	Sub 4	Sub 5	Sub 6	Sub 7	total
Var 1	32	28	28	25	28	23	33	197
Var 2	29	16	21	23	19	13	21	142
Var 3	34	31	28	26	29	33	34	215
Var 4	33	15	22	23	19	27	21	160
Pref.	3,4,1,2	3,1,2,4	1,3,4,2	3,1,2,4	3,1,2,4	3,4,1,2	3,1,4,2	3,1,4,2

In summary, there was an inverse relationship between time performance and error performance; the faster the time, the higher the error. Variations with smaller haptics were faster to complete, possibly because the physical length of the path was less than that for the larger haptics. Graphics, when large, also allowed subjects to easily navigate through the maze. There was a perception of more space and fewer constraints when subjects were presented with large graphics.

5.3.2 Experiment 2: Tests Speed, With Visual and Haptic Guidance

In this experiment, the subjects were told to minimize the time to completion and to use the walls of the maze as a guide to complete the maze. Five training trials were given followed by 40 random trials of the four variations.

Table 5-5 shows the mean time performance for the five subjects in Experiment 2. Subject 3 required much more time to complete the mazes than any of the other subjects for experiments 2, 3, and 4. This subject was the subject who had outlayer data in Experiment 1. The boxplots of the results with all five subjects can be seen in Appendix B. The following discussion is based on the statistics calculated with subjects 1, 2, 4, and 5. The trends among the variations were the same for both four subjects and five subjects, though the variance in the data was less for four subjects.

Variation 3, with small haptics and large graphics, had the fastest time performance, 6.0 ± 0.2 seconds. Variation 4, with small haptics and small graphics, followed closely with an average time performance of 6.1 ± 0.2 seconds. Figure 5-3 shows the boxplot of the time results.

Variation 1, with large haptics and large graphics had the next fastest completion time,

Table 5.5: Mean Time Performance for Experiment 2: Speed, Visual and Haptic Feedback

	Var 1 (sec)	Var 2 (sec)	Var 3 (sec)	Var 4 (sec)	pref.
Subject 1	6.3	6.7	5.4	5.5	3,4,1,2
Subject 2	6	6.1	5.3	5.1	4,3,1,2
Subject 3 *	18.7	20.2	16.2	16.5	3,4,1,2
Subject 4	8.6	9	7.6	8.3	3,4,1,2
Subject 5	6.7	7	5.7	5.5	4,3,1,2
Statistics with 5 Subjects					
Average	9.3 ± 0.7	9.8 ± 0.8	8.0 ± 0.6	8.2 ± 0.6	3,4,1,2
Median	7.1	7.3	6	5.8	4,3,1,2
Statistics with Subjects 1,2,4,5					
Average (4)	6.9 ± 0.2	7.2 ± 0.2	6.0 ± 0.2	6.1 ± 0.2	3,4,1,2
Median (4)	6.9	7.2	5.7	5.6	4,3,1,2

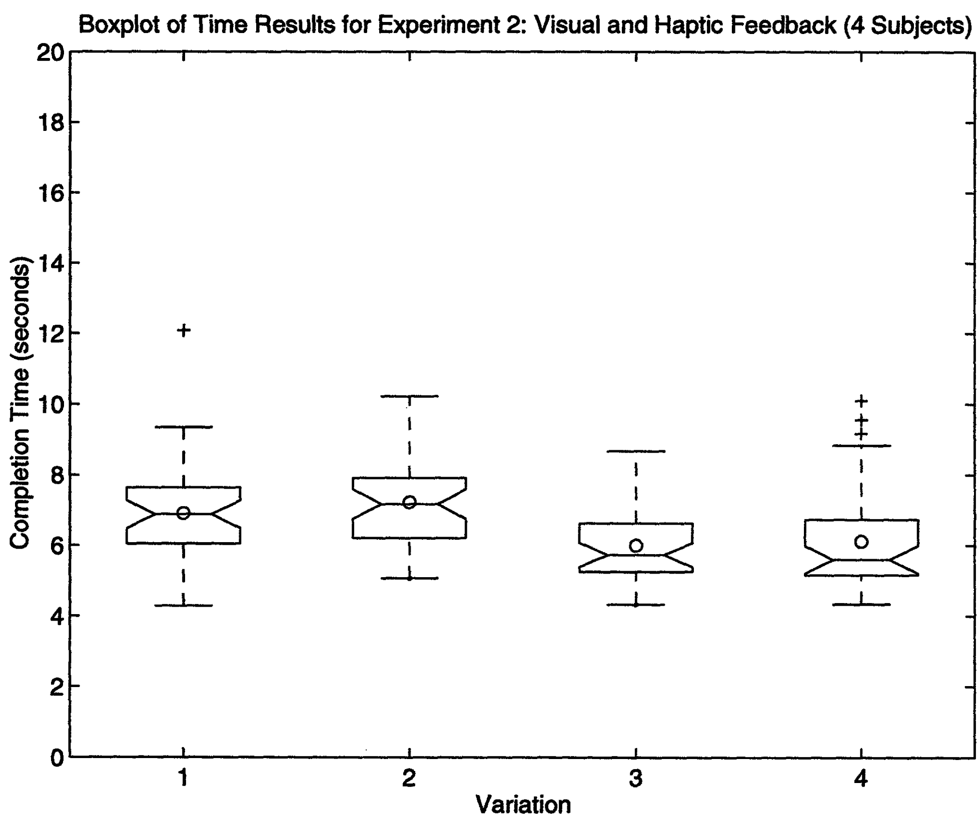


Figure 5-3: Boxplot of the time results for Experiment 2: Speed, Visual and Haptic Feedback. Variation 1: mean = 6.9 ± 0.2, median = 6.9. Variation 2: mean = 7.2 ± 0.2, median = 7.2. Variation 3: mean = 6.0 ± 0.2, median = 5.7. Variation 4: mean = 6.1 ± 0.2, median = 5.6. (sec)

6.9 ± 0.2 seconds. Variation 2 had the slowest completion time, 7.2 ± 0.2 seconds. Based on the median times, the variations were ranked as 4, 3, 1, and 2 with times of 5.6, 5.7, 6.9 and 7.2 seconds respectively.

Since the walls of the maze were not infinitely stiff, subjects were able to pass through the walls if too much force was applied. There was a total of zero wall crossing errors for Variation 1, two for Variation 2, eight for Variation 3, and four for Variation 4. Variation 3, with small haptics and large graphics, had a large number of wall crossing errors. This can be explained as an effect of visual dominance. When subjects touched the walls of the maze, the wall felt less stiff than if the haptics and graphics were the same size. Since the graphics were larger than the haptics, the subjects thought they had more room to move through than they actually did.

Table 5-6 shows the preference rankings for the variations in Experiment 2. Variation 4, with small haptics and small graphics, was rated easiest to use by three out of five subjects. One subject rated Variations 1 and 3 equally as the easiest to use, indicating a preference for large graphics. Subject 5 rated Variations 1, 3, and 4 as equally easy to use. In general, Variation 2 with large haptics and small graphics was rated the most difficult to use.

Table 5.6: Preference Rankings for Experiment 2: Speed, Visual and Haptic Feedback

Var	Subject 1	Subject 2	Subject 3	Subject 4	Subject 5	Total
1	34	33	46	48	23	184
2	34	30	40	41	15	160
3	30	37	47	48	29	191
4	37	40	45	44	30	196
Pref	4,3,2,1	4,3,1,2	3,1,4,2	(13),4,2	4,3,1,2	4,3,1,2

5.3.3 Experiment 3: Tests Speed, Without Visual Cursor Guidance

In Experiment 3, subjects were told to minimize the time to completion and to use the walls of the maze as a guide. They were presented with a visual display of the maze without the visual cursor update. This forced the subjects to rely on their haptic sense. Table 5-7 shows the mean time performance results for Experiment 3.

Variation 4, with small haptics and small graphics, was completed the fastest on average, 7.4 ± 0.4 seconds. Variation 3, with small haptics and large graphics, was only slightly

Table 5.7: Mean Time Performance Times for Experiment 3: Speed, Haptic Feedback Only

	Var 1 (sec)	Var 2 (sec)	Var 3 (sec)	Var 4 (sec)	ranking
Subject 1	7.4	9.2	7.4	5.8	4,3,1,2
Subject 2	7.4	10.4	8.2	6	4,1,3,2
Subject 3	17.8	20.9	12.9	13.3	3,4,1,2
Subject 4	11.6	11.8	9.4	11.1	3,4,1,2
Subject 5	6.9	7.9	5.4	7	3,1,4,2
Statistics with 5 Subjects					
Average	10.2 ± 0.7	12 ± 0.9	8.6 ± 0.4	8.6 ± 0.5	4,3,1,2
Median	8.2	10.2	8.3	7.6	4,1,3,2
Statistics with Subjects 1,2,4,5					
Average (4)	8.3 ± 0.4	9.7 ± 0.5	7.6 ± 0.4	7.4 ± 0.4	4,3,1,2
Median (4)	7.7	9.3	7.6	6.7	4,3,1,2

behind with a time of 7.6 ± 0.4 seconds followed by Variation 1, with large haptics and large graphics, at a time of 8.3 ± 0.4 seconds. Variation 2, with large haptics and small graphics, required the most time to complete, 9.7 ± 0.5 seconds. The median times were in the same performance order as the mean times with 6.7, 7.6, 7.7, and 9.3 seconds for Variations 4, 3, 1, and 2 respectively. Figure 5-4 shows a boxplot of the time results for Experiment 3.

Since the walls of the maze were not infinitely stiff, subjects were able to pass through the walls if too much force was applied. There was a total of 3 wall crossing errors for Variation 1, 6 for Variation 2, 17 for Variation 3, and 7 for Variation 4. The wall crossing errors were very high for Variations 3. As explained earlier for Experiment 2, this was probably an effect of visual dominance. In general, the wall crossing errors were higher for this experiment than for Experiment 2. This was because this experiment required the subjects to stay in contact with the wall of the maze. The longer they stayed in contact with the wall, the more likely they were to make a wall crossing error.

Table 5-8 shows the preference rankings for the variations in Experiment 3. Variation 1, with large haptics and large graphics, was rated easiest by a wide margin. Variation 4 with small graphics and small haptics was then rated next easiest. Variation 2 was followed by Variation 3 for ease of use.

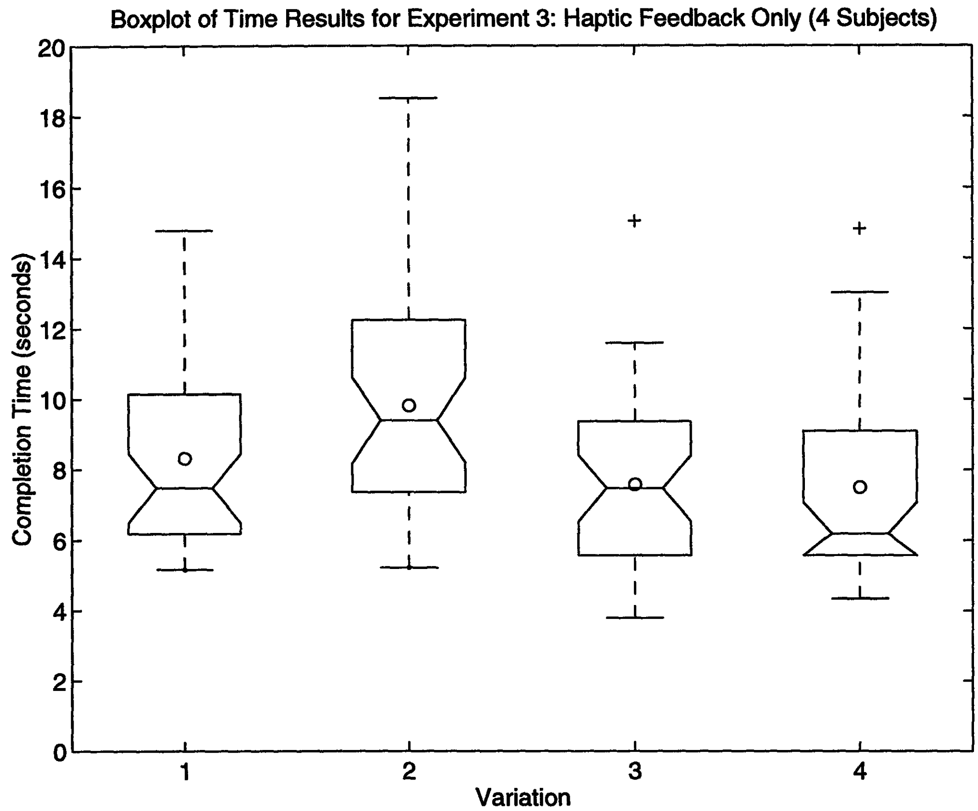


Figure 5-4: Boxplot of the time results for Experiment 3: Speed, Haptic Feedback Only. Variation 1: mean = 8.3 ± 0.4, median = 7.7. Variation 2: mean = 9.7 ± 0.5, median = 9.3. Variation 3: mean = 7.6 ± 0.4, median = 7.6. Variation 4: mean = 7.4 ± 0.4, median = 6.7. (sec)

Table 5.8: Preference Rankings for Experiment 3: Haptic Feedback Only

	Subject 1	Subject 2	Subject 3	Subject 4	Subject 5	Total
Variation 1	35	26	37	42	32	172
Variation 2	30	20	34	39	29	152
Variation 3	35	21	40	33	12	141
Variation 4	36	23	38	33	28	158
Preference	(4(31))2	1,4,3,2	3,4,1,2	1,2,3,4	1,2,4,3	1,4,2,3

5.3.4 Experiment 4: Tests Speed, Without Haptic Guidance

In Experiment 4, subject were told to minimize completion time and to stay on the path of the maze. They were presented with the maze and the cursor visually but given no haptic feedback when they touched the walls of the maze. Table 5-9 shows the mean time performance for Experiment 4.

Table 5.9: Mean Time Performance for Experiment 4: Speed, Visual Feedback Only

	Var 1 (sec)	Var 2 (sec)	Var 3 (sec)	Var 4 (sec)	ranking
Subject 1	9.4	10.6	8.5	8.7	3,4,1,2
Subject 2	13.2	14.1	12.5	12.3	4,3,1,2
Subject 3	20.6	22.5	18.8	18.2	4,3,1,2
Subject 4	12.7	12.5	10.7	10.8	3,4,2,1
Subject 5	8.4	9.2	7.5	7.2	4,3,1,2
Statistics with 5 Subjects					
Average	12.9 ± 0.6	13.8 ± 0.7	11.6 ± 0.6	11.5 ± 0.5	4,3,1,2
Median	12.2	12.5	10.9	10.8	4,3,1,2
Statistics with Subjects 1,2,4,5					
Average (4)	10.1 ± 0.4	10.7 ± 0.3	9.0 ± 0.3	8.9 ± 0.3	4,3,1,2
Median (4)	9.5	10.6	8.4	8.7	3,4,1,2

Subjects completed Variation 4, with the small haptics and small graphics, the fastest with an average time of 8.9 ± 0.3 seconds. There was no significant difference in the completion time between Variation 4 and Variation 3 (9.0 ± 0.3 seconds), both of which had a small haptic workspace. There was also no significant difference in completion times for Variations 1 and 2, with times of 10.1 ± 0.4 and 10.7 ± 0.3 seconds respectively. Variations 1 and 2 required 10 to 20% more time to complete than Variations 3 and 4. Comparing between variations with a large haptic size, the one which also had a small visual size required 8-10% more time than the one with a large visual size. The ranking based on median time is Variation 3, 4, 1, and 2 with completion times of 8.4, 8.7, 9.5, and 10.6 seconds. Figure 5-5 shows the boxplot of the completion times for Experiment 4.

There were no wall crossing errors for Experiment 4. Since the subjects only had visual feedback, and they were told to stay within the path of the maze, no one strayed off course to make a wall crossing error.

Table 5-10 shows the preference rankings for the variations in Experiment 4. Subjects generally preferred large visual displays to small visual displays.

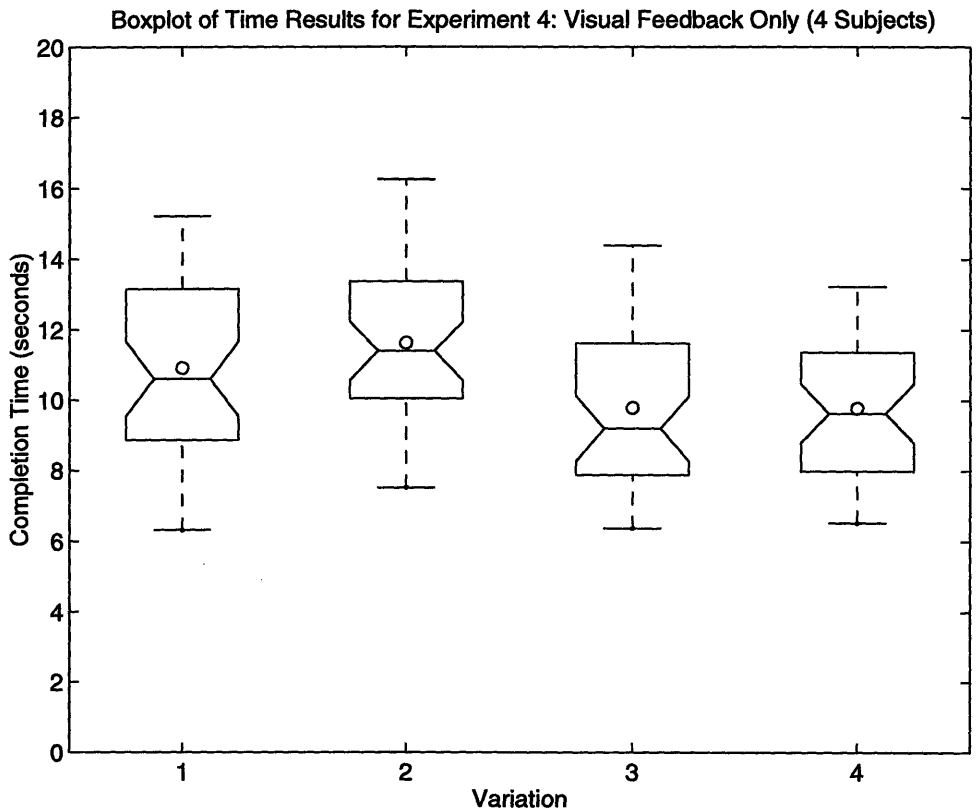


Figure 5-5: Boxplot of the time results for Experiment 4: Speed, Visual Feedback Only. Variation 1: mean = 10.1 ± 0.4, median = 9.5. Variation 2: mean = 10.7 ± 0.3, median = 10.6. Variation 3: mean = 9.0 ± 0.3, median = 8.4. Variation 4: mean = 8.9 ± 0.3, median = 8.7. (sec)

Table 5.10: Preference Rankings for Experiment 4: Speed, Visual Feedback Only

	Subject 1	Subject 2	Subject 3	Subject 4	Subject 5	Total
Variation 1	32	32	40	46	27	177
Variation 2	25	19	33	42	18	137
Variation 3	27	32	40	47	34	180
Variation 4	30	17	36	41	29	153
Pref	1,4,3,2	1,3,2,4	1,3,4,2	3,1,2,4	3,4,1,2	3,1,4,2

5.4 Visual Scaling Effects on Training

In the visual scaling experiments, the mazes all had the same haptic workspace size but had different visual workspace sizes. In one experiment, the subjects were trained on a small visual workspace. In the other experiment, the subjects were trained on a large visual workspace. Table 5-11 lists the variations used in this set of experiments. The subjects were told to minimize contact with the walls in both visual scaling experiments. There were a total of 14 subjects, seven subjects for the increasing visual scale experiment, and seven different subjects for the decreasing visual scale experiment.

Table 5.11: Visual Scaling Variations

	Visual-Haptic Ratio	Name
Variation 5	1:1	Small
Variation 6	1.5:1	Medium
Variation 7	2:1	Large
Variation 8	2.5:1	Ex-Large

5.4.1 Experiment 5: Increasing Visual Scale

In this experiment, the subjects were trained on a small visual workspace. Table 5-12 shows the mean time performance results for seven subjects.

Table 5.12: Mean Time Performance for Experiment 5: Increasing Visual Scale

	Small	Medium	Large	Ex-large	
	Var 5 (sec)	Var 6 (sec)	Var 7 (sec)	Var 8 (sec)	Pref
Subject 1	38	39	34	36	7,8,5,6
Subject 2	14.4	13.8	14.1	13.5	8,6,7,5
Subject 3	14.4	12.6	12.6	12.4	8,7,6,5
Subject 4	12	11.7	10.9	11.5	7,8,6,5
Subject 5	35.4	32.7	27.7	27.4	8,7,6,5
Subject 6	13.9	13.5	13.7	13.9	6,7,8,5
Subject 7	28.4	26.4	23.2	22.7	8,7,6,5
Average	22.4 ± 1.2	21.4 ± 1.2	19.5 ± 0.9	19.6 ± 1.0	7,8,6,5
Median	16.3	14.2	15.5	15.4	6,8,7,5

Variation "Large" had the fastest mean time for completion, 19.5 ± 0.9 seconds . Variation "Ex-large" was second fastest with 19.6 ± 1.0 seconds, followed by Variation "Medium" with 21.4 ± 1.2 seconds. Variation "Small" was slowest with a mean completion time of 22.4 ± 1.2 seconds. The mean time and standard deviations showed that there was very little difference among the four size variations. However, the median values of the variations showed that there was a significant improvement in performance time between "Small" and "Medium", which had completion times of 16.3 seconds and 14.2 seconds respectively, and a distinct decrease in performance as the visual size increased. The completion time dropped from 14.2 seconds to 15.5 seconds and 15.4 seconds for Variation "Medium" to Variation "Large" and Variation "Ex-large" respectively. Figure 5.6 shows a boxplot of the time performance for the increased visual scaling experiment.

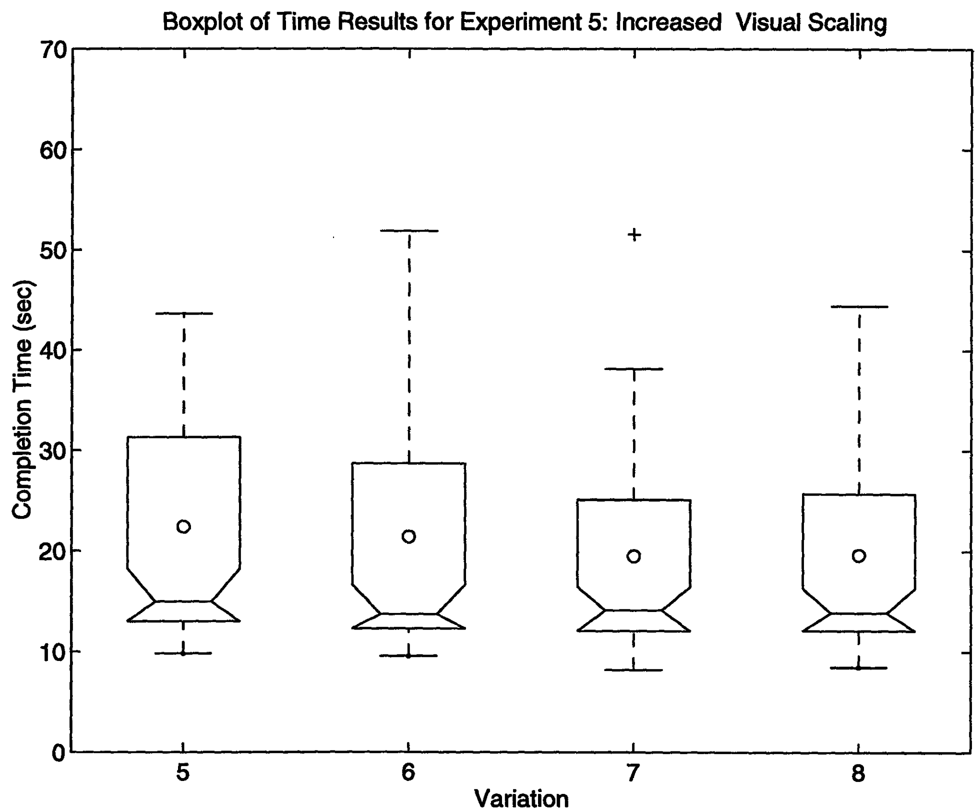


Figure 5-6: Boxplot of the time results for Experiment 5: Increasing Visual Scale. Variation 5 ("Small"): mean = 22.4 ± 1.2, median = 16.3. Variation 6 ("Medium"): mean = 21.4 ± 1.2, median = 14.2. Variation 7 ("Large"): mean = 19.5 ± 0.9, median = 15.5. Variation 8 ("Ex-large"): mean = 19.6 ± 1.0, median = 15.4. (sec)

Table 5-13 shows the mean error for the size variations presented to the seven subjects in Experiment 5. Variation "Medium" had the least amount of error on average, 319 ± 40. Variation "Ex-large" had the next lowest amount of error with 326 ± 46, followed by Variation "Large" with 335 ± 42. Variation "Small" had the most amount of error with 406

± 47 counts. Ordering according to the median values was the same: Variation "Medium" had the least amount of error followed by "Ex-large", "Large", and "Small," with of error counts of 143, 160, 180, and 217 respectively. There were several trials in which the subjects had no errors. Variation "Small" had 12 trials, "Medium" had 18 trials, "Large" had 19 trials, and "Ex-large" had 24 trials with no errors. Figure 5-7 shows a boxplot of the error results for the increased visual scaling experiment.

Table 5.13: Mean Error Performance for Experiment 5: Increasing Visual Scale

	Small	Medium	Large	Ex-large	
	Var 5	Var 6	Var 7	Var 8	Pref
Subject 1	155	41	21	50	7,6,8,5
Subject 2	885	693	897	888	6,5,8,7
Subject 3	330	215	153	143	8,7,6,5
Subject 4	405	338	417	386	6,8,5,7
Subject 5	123	67	119	136	6,7,5,8
Subject 6	901	855	706	666	8,7,6,5
Subject 7	45	29	29	15	8,6,7,5
Average	406 ± 47	319 ± 40	335 ± 42	326 ± 46	6,8,7,5
Median	217	143	180	160	6,8,7,5
no error trials	12	18	19	24	8,7,6,5

There were no wall crossing errors in this experiment since the subjects were told to minimize wall contact.

Table 5-14 shows the results of the preference rankings of the variations for Experiment 5. Subjects consistently and unanimously ranked Variation "Ex-large" as the easiest to complete and Variation "Small" as the hardest to complete. Most subjects ranked strictly according to size. However, two subjects found Variation "Medium" to be easier than Variation "Large".

Table 5.14: Preference Rankings for Experiment 5: Increasing Visual Scale

Var	Sub 1	Sub 2	Sub 3	Sub 4	Sub 5	Sub 6	Sub 7	Total
5) Small	14	28	10	25	14	22	17	130
6) Medium	21	31	25	32	22	25	23	179
7) Large	28	30	26	29	27	30	28	198
8) Ex-large	29	33	31	35	32	34	32	226
Pref.	8,7,6,5	8,6,7,5	8,7,6,5	8,6,7,5	8,7,6,5	8,7,6,5	8,7,6,5	8,7,6,5

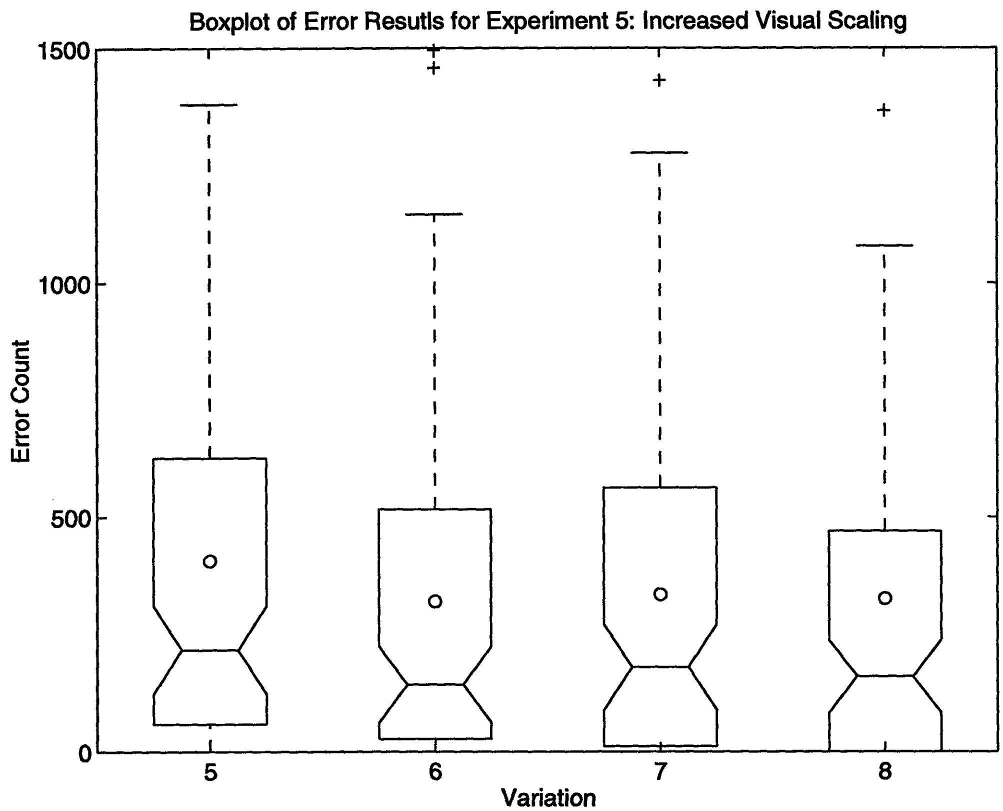


Figure 5-7: Boxplot of the error results for Experiment 5: Increasing Visual Scale. Variation 5 ("Small"): mean = 406 ± 47, median = 217. Variation 6 ("Medium"): mean = 319 ± 40, median = 143. Variation 7 ("Large"): mean = 335 ± 42, median = 180. Variation 8 ("Ex-large"): mean = 326 ± 46, median = 160. (counts)

5.4.2 Experiment 6: Decreasing Visual Scale

In this experiment, subjects were trained on the "Ex-large" visual size and told to minimize contact with the walls of the maze. Table 5-15 shows the mean time required to complete each of the variations for Experiment 6. Subject 7 required much more time to complete the mazes than the rest of the subjects. The boxplot of the results with seven subjects is shown in Appendix B. Most of the trials for subject 7 were outside the range of data. A new analysis was made without subject 7. The following discussion was based on the results with six subjects.

Table 5.15: Mean Time Performance for Experiment 6: Decreasing Visual Scale

	Small	Medium	Large	Ex-large	
	Var 5 (sec)	Var 6 (sec)	Var 7 (sec)	Var 8 (sec)	Pref
Subject 1	33.8	29.7	27.7	26.5	8,7,6,5
Subject 2	24.5	22.5	19.8	18.3	8,7,6,5
Subject 3	18.7	18.7	18.4	18.7	7,8,6,5
Subject 4	29.6	29.5	27.8	28.4	7,8,6,5
Subject 5	16.7	16.6	15.3	14.2	8,7,6,5
Subject 6	23.3	20.2	16.9	17	7,8,6,5
Subject 7 *	63.4	56.5	41.7	41.7	8,7,6,5
Statistics with 7 Subjects					
Average	30.0 ± 1.9	27.7 ± 1.6	23.9 ± 1.1	23.5 ± 1.0	8,7,6,5
Median	24.7	23.9	19.9	19.5	8,7,6,5
Statistics with Subjects 1,2,3,4,5,6					
Average (6)	23.4 ± 1.1	22.3 ± 0.8	20.4 ± 0.8	20.1 ± 0.7	8,7,6,5
Median (6)	23.5	21.3	18.5	18.8	7,8,6,5

For most subjects there was a significant improvement in time as the visual size increased from "Small" to "Medium", and "Medium" to "Large." There was, however, no significant improvement when the visual size was increased from "Large" to "Ex-large." Both the mean time and the median time showed this trend. Variation "Small" had a mean completion time of 23.4 ± 1.1 seconds. Variation "Medium" had a mean time of 22.3 ± 0.8 seconds. Variation "Large" had a mean time of 20.4 ± 0.8 seconds. Variation "Ex-large" had a mean time of 20.1 ± 0.7 seconds. The median times were 23.5, 21.3, 18.8, and 18.5 seconds for "Small", "Medium", "Ex-large", and "Large" respectively. Figure 5-8 shows the boxplot for the time results of Experiment 6.

Table 5-16 shows the mean error results for Experiment 6. The error counts did not

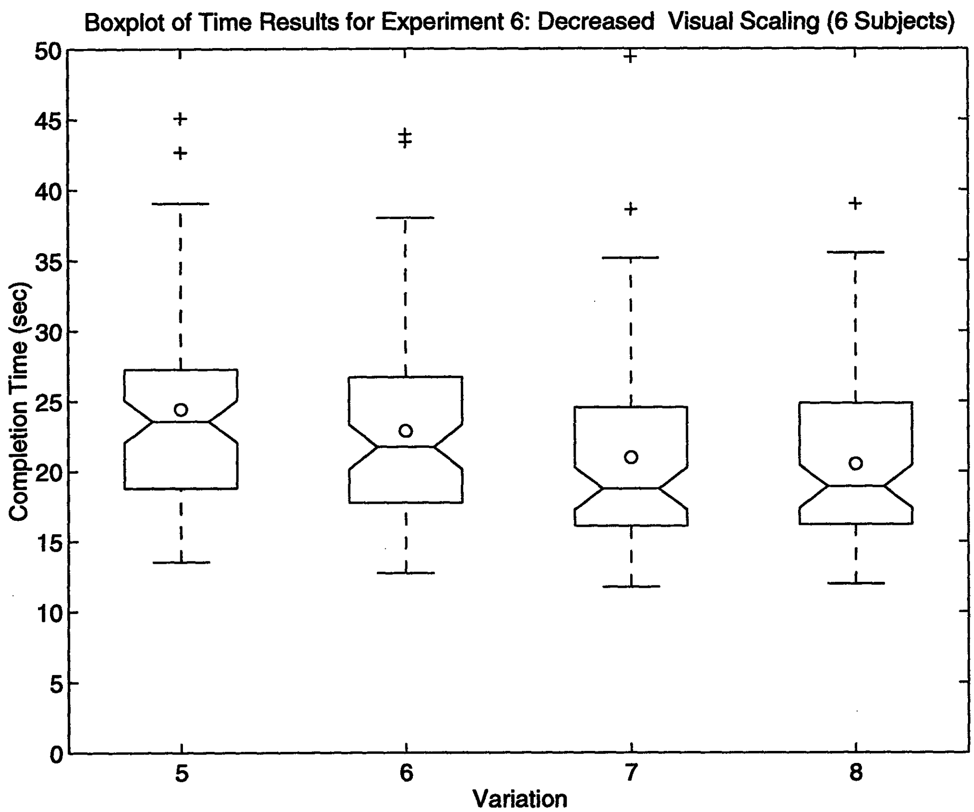


Figure 5-8: Boxplot of the time results for Experiment 6: Decreasing Visual Scale. Variation 5 ("Small"): mean = 23.4 ± 1.1, median = 23.5. Variation 6 ("Medium"): mean = 22.3 ± 0.8, median = 21.3. Variation 7 ("Large"): mean = 20.4 ± 0.8, median = 18.5. Variation 8 ("Ex-large"): mean = 20.1 ± 0.7, median = 18.8. (sec)

vary linearly with increasing visual size. Variation "Large" had the lowest error count at 138 ± 20, followed by Variation "Medium" with 148 ± 26. Variation "Ex-large" had the next lowest error count, 176 ± 32. Variation "Small" had the highest error count, 191 ± 39. The median values for the error count had a trend different from the mean value. Variation "Small" had the lowest at 62 counts, followed by variation "Medium" with 73 counts, then by variation "Large" with 75 counts. Variation "Ex-large" had the highest median error at 86 counts. Figure 5-9 shows the boxplot for the error results of Experiment 6. There were many trials in which subjects performed without any error. Variation Large had the most trials without errors, 26 trials. Variation "Medium" had 23 no error trials, followed by Variation "Ex-large" with 19 trials, and Variation "Small" with 14 trials.

There were no wall crossing errors in this experiment since the subjects were told to minimize wall contact.

Table 5.16: Mean Error Performance for Experiment 6: Decreasing Visual Scale

	Small	Medium	Large	Ex-large	
	Var 5	Var 6	Var 7	Var 8	Pref
Subject 1	185	270	189	173	8,5,7,6
Subject 2	31	12	12	12	7,6,8,5
Subject 3	510	300	274	541	7,6,5,8
Subject 4	277	190	205	123	8,6,7,5
Subject 5	74	67	94	129	6,5,7,8
Subject 6	68	47	51	76	6,7,5,8
Subject 7 *	3	33	19	4	5,8,7,6
Statistics with 7 Subjects					
Average	164 ± 34	131 ± 22	121 ± 18	151 ± 29	7,6,8,5
Median	33	58	22	45	7,5,8,6
no error trials	26	34	39	32	7,6,8,5
Statistics with Subjects 1,2,3,4,5,6					
Average (6)	191 ± 39	148 ± 26	138 ± 20	176 ± 32	7,6,8,5
Median (6)	62	73	75	86	5,6,7,8
no error trials	14	23	26	19	7,6,8,5

Table 5-17 shows the preference ranking for the variations in Experiment 6. The subjects consistently preferred lager visual mazes to smaller visual mazes. In the comments given in the post-session survey, subjects said, "the larger mazes were easier...there was more room to move in."

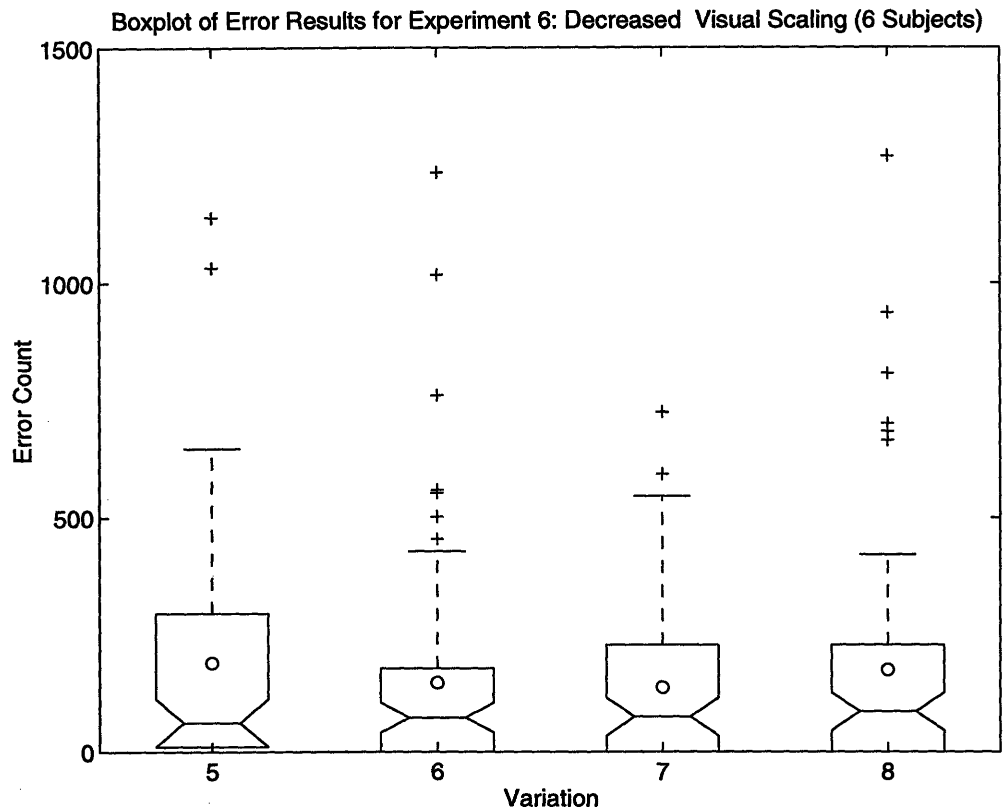


Figure 5-9: Boxplot of the error results for Experiment 6: Decreasing Visual Scale. Variation 1 ("Small"): mean = 191 ± 39, median = 62. Variation 2 ("Medium"): mean = 148 ± 26, median = 73. Variation 3 ("Large"): mean = 138 ± 20, median = 75. Variation 4 ("Ex-large"): mean = 176 ± 32, median = 86. (counts)

Table 5.17: Preference Rankings for Experiment 6: Decreasing Visual Scale

Var	Sub 1	Sub 2	Sub 3	Sub 4	Sub 5	Sub 6	Sub 7	Total
5) Small	16	7	23	14	33	16	18	127
6) Medium	18	21	27	19	35	23	24	167
7) Large	24	32	31	30	35	29	29	210
8) Ex-large	31	35	32	29	35	35	34	231
Preference	8,7,6,5	8,7,6,5	8,7,6,5	7,8,6,5	8,7,6,5	8,7,6,5	8,7,6,5	8,7,6,5

5.5 Cursor Paradigms

Table 5-18 lists the characteristics for each of the cursor paradigms used in Experiment 7.

Table 5.18: Cursor Paradigms

Analogy	"mouse"	"magnifying lens"	"tele-video"	"RC car"
Paradigm	1	2	3	4
Visual Cursor	moving	static	static	moving
Visual Environment	static	moving	moving	static
Haptic Cursor	moving	moving	static	static
Haptic Environment	static	static	moving	moving
Control Type	Position Control	Position Control	Force Control	Force Control

5.5.1 Experiment 7: Position and Force Control Cursor Paradigms

In this experiment, the subjects were told to complete mazes as quickly as possible without passing through the walls. Table 5-19 shows the time required to complete the paradigms presented in Experiment 7.

Table 5.19: Mean Time Performance for Experiment 7: Cursor Control Paradigms

	Para 1 (sec)	Para 2 (sec)	Para 3 (sec)	Para 4 (sec)	Pref.
Subject 1	10	24	60	38	1,2,4,3
Subject 2	13.7	20.1	36.3	34.9	1,2,4,3
Subject 3	14	21	28	24	1,2,4,3
Subject 4	10.4	11.7	36.5	31.4	1,2,4,3
Subject 5	7.4	9.9	31.1	28.3	1,2,4,3
Subject 6	9.6	13.4	25.1	24.3	1,2,4,3
Subject 7	10.4	17.4	34.3	20.4	1,2,4,3
Average	10.8 ± 0.3	16.1 ± 0.7	33.4 ± 1.0	27.3 ± 0.6	1,2,4,3
Median	9.7	15.1	32.2	27.1	1,2,4,3

Position control paradigms required significantly less time to complete than the force control paradigms. The "mouse" paradigm required the least amount of time to complete, 10.8 ± 0.3 seconds, followed by the "magnifying lens" paradigm with 16.1 ± 0.7 seconds. Subjects completed the position control paradigms in less than half the time of the force control paradigms. The "RC car" paradigm averaged 27.3 ± 0.6 seconds to complete. The "tele-video" paradigm had the highest mean completion time, 33.4 ± 1.0 seconds. The trend for the median values of the four paradigms was consistent with the trend for the mean values. The median times were 9.7, 15.1, 27.1 and 32.2 seconds for the "mouse" paradigm, "magnifying lens" paradigm, "RC car" paradigm, and "tele-video" paradigm respectively. Figure 5-10 shows the boxplot of the time results for the cursor control paradigm experiment.

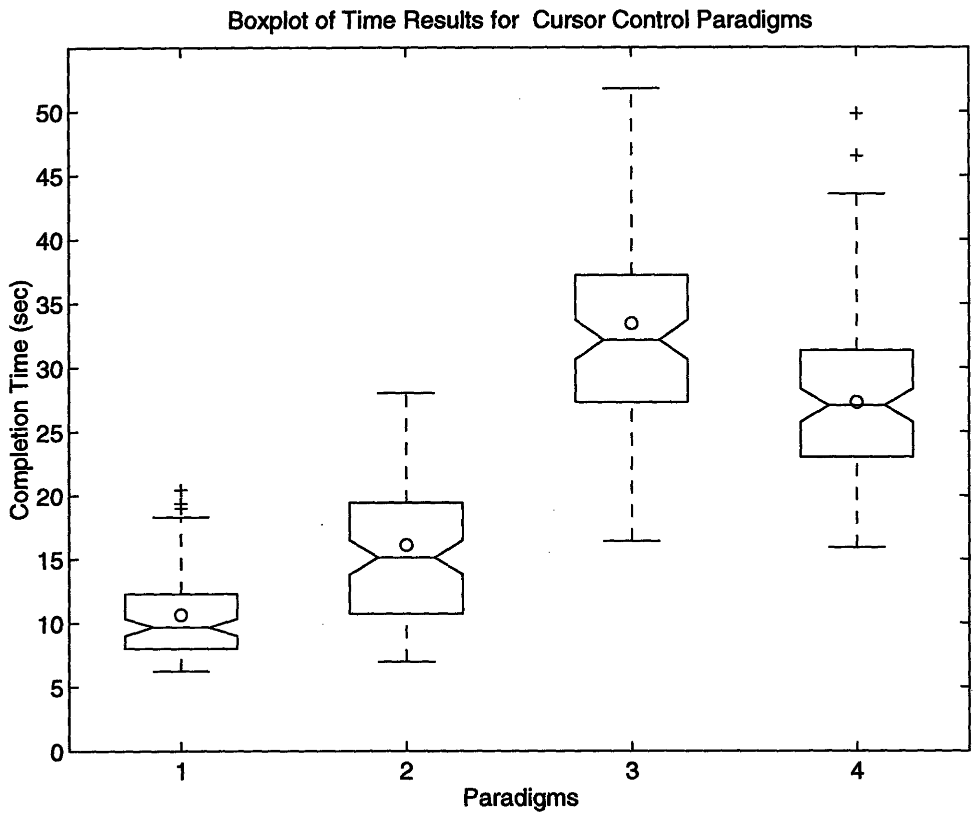


Figure 5-10: Boxplot of the time results for Experiment 7: Cursor Control Paradigm. Paradigm 1 ("mouse"): mean = 10.8 ± 0.3, median = 9.7. Paradigm 2 ("lens"): mean = 16.1 ± 0.7, median = 15.1. Paradigm 3 ("video"): mean = 33.4 ± 1.0, median = 32.2. Paradigm 4 ("RC car"): mean = 27.3 ± 0.6, median = 27.1. (sec)

There were zero wall errors for the "mouse" Paradigm, zero for the "magnifying lens" Paradigm, 53 for the "tele-video" Paradigm, and 35 for the "RC car" Paradigm. Since the force control cursor paradigm was new to the subjects, some found it quite difficult to control; hence, the numerous wall crossing errors. Many subjects also found the "tele-video" paradigm most difficult of the paradigm since visual scene was not stationary. Several subjects found the moving visual scene distracting.

Table 5-20 shows the preference rankings of the cursor paradigms for Experiment 7. Overall, the subjects found the "mouse" paradigm easiest, then the "lens", "RC car", and finally the "tele-video" paradigm. This was the exact same order as that of time performance. Some of the subjects found "tele-video" to be easier than "RC car" because it had an analogous movement of cursor and environment. Most subjects found "RC car" to be easier because they liked a stationary background.

Table 5.20: Preference Rankings for Experiment 7: Cursor Control Paradigms

	Sub 1	Sub 2	Sub 3	Sub 4	Sub 5	Sub 6	Sub 7	Avg
1) Mouse	73	73	74	74	75	72	74	74
2) Lens	59	60	60	66	53	42	57	57
3) Video	43	45	46	38	31	34	42	40
4) RC car	31	45	44	49	39	36	54	43
Preference	1,2,3,4	1,2,3,4	1,2,3,4	1,2,4,3	1,2,4,3	1,2,4,3	1,2,4,3	1,2,4,3

Given the two position control and two force control cursor paradigms, subjects found position control to be much easier than force control. The ratings found the "mouse" paradigm to be easiest over all, followed by "magnifying lens". The force control cursor paradigms were equally rated, with some subjects preferring "tele-video" paradigm and some subjects preferring "RC car" Paradigm. Most found "tele-video" paradigm easier for the force control because the correlation of the cursor to the environment was more consistent among the visual and haptic displays. This paradigm had a stationary haptic cursor and a stationary visual cursor.

Chapter 6

Discussion

6.1 Visual-Haptic Size Experiments

6.1.1 Accuracy and Speed

Subjects performed best and felt most at ease when presented with a small haptic workspace corresponding to a large visual workspace. This allowed them to take advantage of their fine motor control skills. The large visual presentation let them have an enhanced view of their haptic workspace. However, when presented with such a workspace, the wall did not feel very stiff. This was due to the effect of visual dominance. The walls felt stiffer when the subjects were presented with a small visual workspace coupled with a large haptic workspace. Time to completion was inversely related to the wall contact error count. Subjects were able to complete the maze faster if they stayed in contact with the wall more. Many used a strategy of having the wall as a guide to go straight, then turn in the appropriate direction when they struck an opposing wall.

6.1.2 Sensory Feedback Experiments

Subjects could complete the mazes faster when they were given both visual and haptic cues. When deprived of one of these sensory modes, subjects performed better when given only haptic cues. The results of these experiments showed the importance of having haptic feedback in completing a task. On average, there was a 26% decrease in performance from having both visual and haptic feedback to having only haptic feedback. There was a 61% decrease in performance from having both visual and haptic feedback to having only visual feedback. Figures 6-1 through 6-4 show the boxplot trends of the various sensory feedback modes for Variations 1 though 4, respectively. Performance was much more consistent when subjects were given both visual and haptic feedback. The variance of the quartile data was much less for the visual and haptic feedback than for either of the haptic feedback only or the visual feedback only. Haptic feedback only had the largest variance in quartile data since subjects sometimes became lost in the maze and required more time to complete the navigation.

Subjects preferred and performed best on a small visual and haptic size when given both visual and haptic feedback. Subject preferred a large visual and haptic size, but performed best on a small visual and haptic size for the haptic feedback only experiment. Subjects preferred and performed best on a large visual size and a small haptic size for the visual feedback only experiment. It is unexpected that the subject's performance and preference for a certain variation would change given different sensory feedback modes.

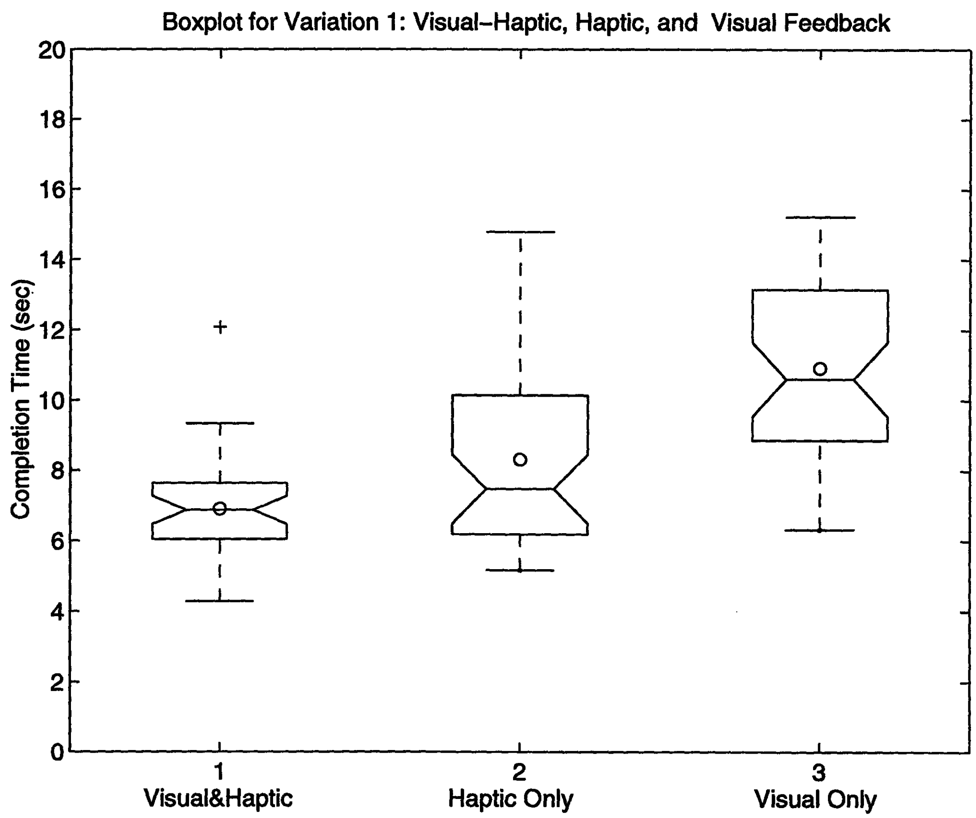


Figure 6-1: Boxplot of Variation 1 for Sensory Feedback Experiments. Visual and Haptic: mean = 6.9 ± 0.2, median = 6.9. Haptic Only: mean = 8.3 ± 0.4, median = 7.7. Visual Only: mean = 10.1 ± 0.4, median = 9.5. (sec)

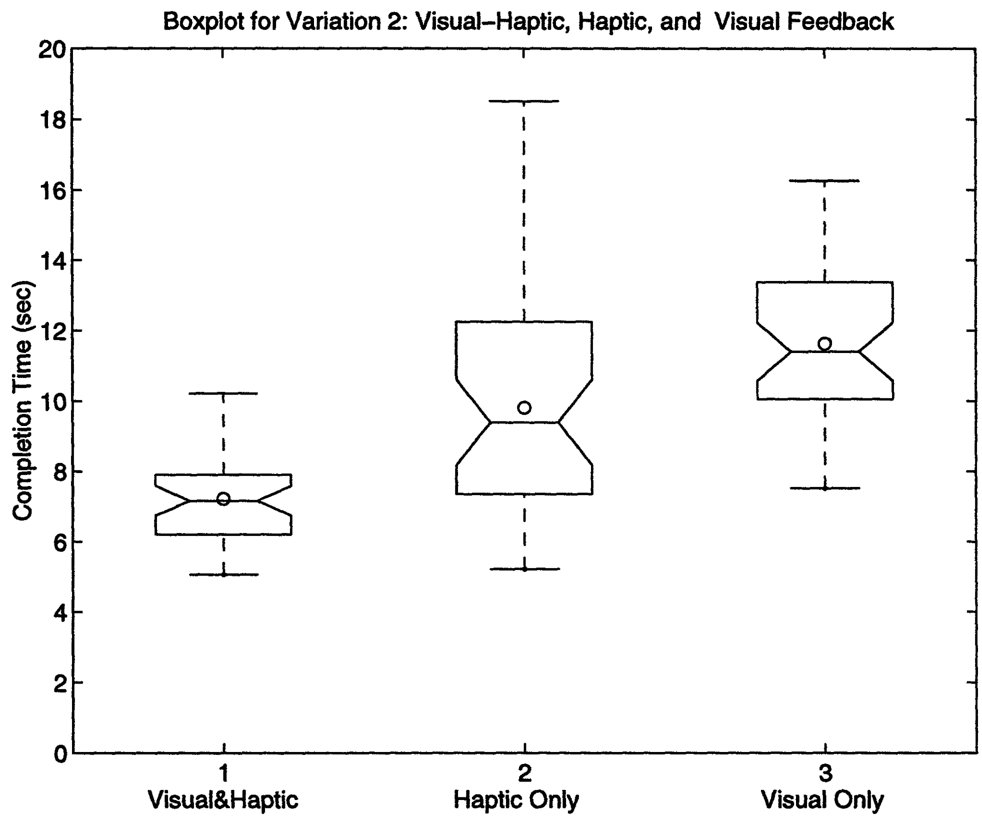


Figure 6-2: Boxplot of Variation 2 for Sensory Feedback Experiments. Visual and Haptic: mean = 7.2 ± 0.2, median = 7.2. Haptic Only: mean = 9.7 ± 0.5, median = 9.3. Visual Only: mean = 10.7 ± 0.3, median = 10.6. (sec)

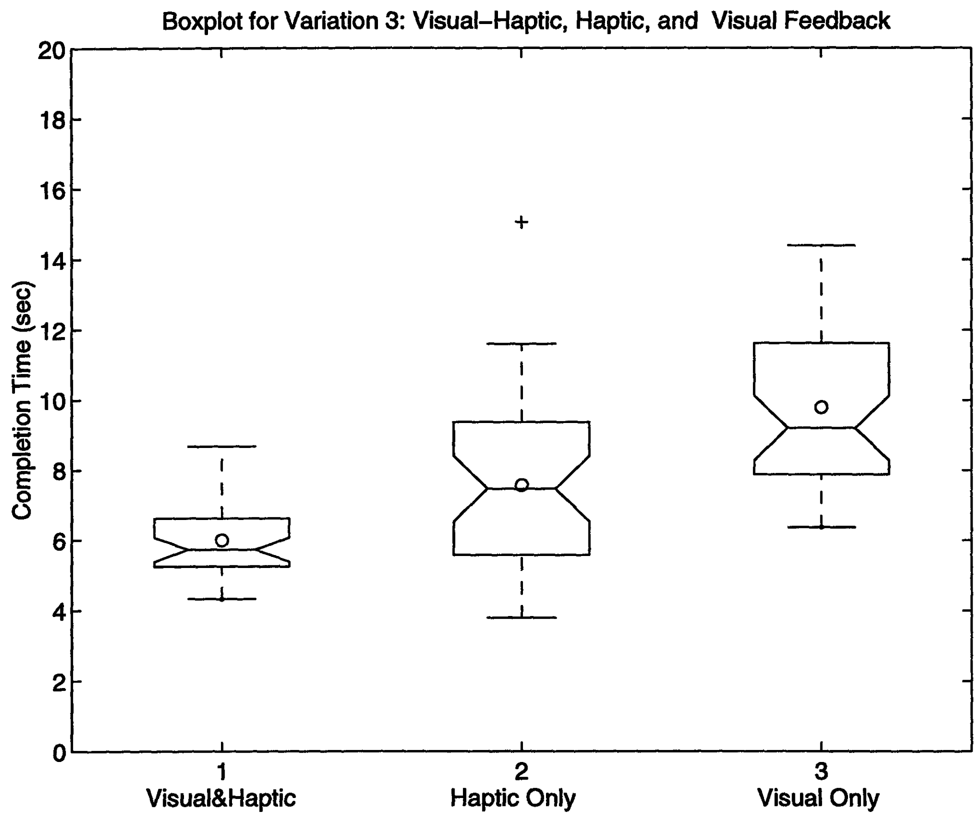


Figure 6-3: Boxplot of Variation 3 for Sensory Feedback Experiments. Visual and Haptic: mean = 6.0 ± 0.2, median = 5.7. Haptic Only: mean = 7.6 ± 0.4, median = 7.6. Visual Only: mean = 9.0 ± 0.3, median = 8.4(sec)

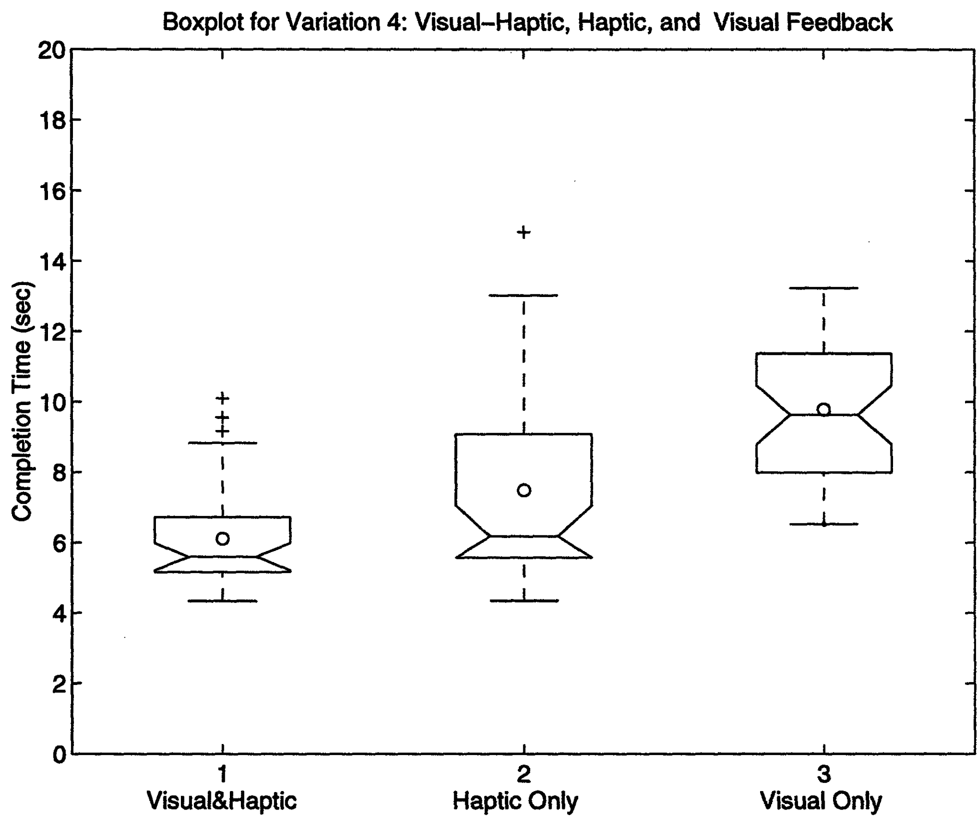


Figure 6-4: Boxplot of Variation 4 for Sensory Feedback Experiments. Visual and Haptic: mean = 6.1 ± 0.2, median = 5.6. Haptic Only: mean = 7.4 ± 0.4, median = 6.7. Visual Only: mean = 8.9 ± 0.3, median = 8.7(sec)

6.2 Visual Scaling Experiments

The results of experiments 1, 2, 3, and 4, showed that subjects preferred and performed best when given a large visual-haptic size ratio. A second set of experiments was designed to test the extent of this phenomenon. Would performance always continue to improve, would performance level off at some critical ratio, or would performance degrade at a critical ratio? In the visual scaling experiments, subjects were presented with various visual workspace sizes and a single haptic workspace size.

When subjects were trained on the largest visual size in the series, their performance improved as the visual workspace size increased. A significant improvement in time to completion was seen as the visual-haptic ratio increased from 1:1 to 1.5:1 and from 1.5:1 to 2:1. However, the improvement in completion time was not as significant as the visual-haptic size ratio increased from 2:1 to 2.5:1. This showed a limit in the effect of visual dominance. Once the visual size was larger than twice the haptic size, the subject's performance no longer improved.

However, when subjects were trained on the smaller visual size in the series, their overall performance did not improve steadily. Some subjects improved steadily, but other subjects improved and then leveled off. Still others improved and then regressed. This also showed that there was a limit in improvement of performance when visual display was magnified. There was a perception of finer motor control when the field of view was magnified.

6.3 Cursor Paradigm Experiment

All the subjects found a position controlled cursor to be much easier to use than a force controlled cursor. All the subjects also preferred the mouse paradigm. This might have been because all the subjects, being university students who work on the computer a fair amount and use the mouse, had already been pre-trained in the use of this position control paradigm and therefore preferred it. The subjects preferred the paradigms in the following order "Mouse", "Magnifying lens", "RC car", and "Tele-video". Their performance was in the same order as their preference.

Most subjects required 50% more time to complete the maze for "magnifying lens" paradigm than "mouse" paradigm. Although both were position control, the paradigm with a higher visual-haptic consistency was easier to complete. Only one subject required only 10% more time.

Force control paradigms required significantly more time to complete than position control paradigms. Most subjects required at least twice as much time, some as much as 6 times that of Paradigm 1. Subjects found force control paradigms more difficult, possibly due the fact that it was a more complex method of control. Not only was precision of motion needed, but precision of force was also needed.

Some subjects found it easier if the visual presentation and the haptic presentation were consistent. In other words, if the visual cursor was moving, it was easier to complete the maze if the haptic cursor was also moving. Also if the visual cursor was stationary, it was easier if the haptic cursor was stationary. Some subjects, however, found it easier if the background was always stationary.

6.4 Ergonomics

Several subjects complained about discomfort in their wrists. The forearm, wrist, and hand must be correctly supported in haptic tasks, especially if the task required the human to use motor control skills for a sustained amount of time. Though the arm rest helped to raise the arm and hand to the correct position for some subjects, it was not ideal for all subjects. It also did not compensate for motion. A stationary arm rest was useful for stationary tasks, but an armrest that can rotate and move would be better for dynamic tasks.

Chapter 7

Conclusions

7.1 MAGIC Toolkit

The MAGIC Toolkit is very useful application that allows a user to quickly and easily create a virtual scene. The library files also allow a user to integrate the virtual scene into the user's specific application. Improvements to the MAGIC Toolkit include the advancement to 3-dimensional graphics, the addition of material properties, and the addition of dynamic properties. Though 2-dimensional graphics suffice for some applications, 3-dimensional graphics are necessary for a more immersive effect. Other material properties that could be added to the object's characteristics include texture, mass, and viscosity. The addition of virtual mechanisms such as pin joints or ball joints would allow dynamic interactions between the objects in the VE.

7.2 Interaction Paradigms

An effect of scaling which may prove useful in making walls or surfaces seem more stiff is to have the visuals of a smaller scale than the haptics. This fact was discovered when several subjects commented on the fact that it is much easier to pass through the wall on some variations than others. When looking over the traces of the subjects, the tendency to pass through the walls was much stronger for visuals that were larger than the haptics. The corollary to this is that smaller visual scales will imitate a stiffer wall. What we already know of visual dominance with the spring experiment, supports this effect [Srinivasan et. al., 1996].

Performance results conflicted with what the subjects perceived. Though subjects found the "mouse" paradigm to be the easiest to use, an improvement could be seen in the completion time of the maze for all cursor paradigms. This means that a person can be trained to use a specific paradigm effectively. The four different cursor paradigms defined in this can be used for a large variety of tasks.

7.3 Future Work

For some tasks, only a small workspace is needed. Future haptic interfaces can be developed with this fact in mind. The implementation of haptic interfaces can take advantage of force control interactions to gain a larger workspace. Further studies on the effectiveness of using force control need to be investigated.

The MAGIC Toolkit can be used to develop sensory tasks for rehabilitative medicine. Improvements in the MAGIC Toolkit include the addition of 3-dimensional graphics, more material properties, and dynamic behavior of objects. This will allow for a broader application of multimodal environments.

Appendix A

Instructions for Experiments

Experiment 1:

Objective: To complete the maze as accurately as possible without touching the walls

Procedure: Before each trial you will be given a blank screen with a circle in the middle. There are two cursors representing your current location. The large yellow cursor is a forward projection of your location. The small white cursor is a right projection of your location. You need to center both of these cursors in the circle before you start. This is to make sure you start at the same spot for every trial.

You hold the stylus in your hand as you would a pencil and rest your forearm in the arm rest. Once you have aligned the cursor you can press any key to start.

A red maze will appear. There will also be a green starting block and a black finishing block. Move the Stylus forward until you feel the front wall. To start, move to the left and touch the green block gently. The block will turn light green. Once you let go, the timer will start and While you are going through the maze, the only surface you should touch is the front surface. Try to minimize contact with any other surface. Once you touch the black finishing block you will be finished with that trial.

There are a total of 62 trials. You will be asked to rank several of the trials on a scale of 1 to 5 on ease of completing the maze half way through the session. (5 being the easiest, 1 being the hardest)

Experiment 2:

Objective: To complete the maze as quickly as possible. You can use the wall of the maze to help guide you along.

Procedure: Before each trial you will be given a blank screen with a circle in the middle. There are two cursors representing your current location. The large yellow cursor is a forward projection of your location. The small white cursor is a right projection of your location. You need to center both of these cursors in the circle before you start. This is to make sure you start at the same spot for every trial.

You hold the stylus in your hand as you would a pencil and rest your forearm in the arm rest. Once you have aligned the cursor you can press any key to start.

A red maze will appear. There will also be a green starting block and a black finishing block. Move the Stylus forward until you feel the front wall. To start, move to the left and touch the green block gently. The block will turn light green. Once you let go, the timer will start and While you are going through the maze, please stay in contact with the front surface. You can use the other wall surfaces to guide you through the maze. Once you touch the black finishing block you will be finished with that trial.

There are a total of 45 trials. You will be asked to rank several of the trials on a scale of 1 to 5 on ease of completing the maze after the 5th trial.
1 = very hard
2 = hard
3 = not too hard, not too easy
4 = easy
5 = very easy

Experiment 3:

Objective: To complete the maze as quickly as possible. You can use the wall of the maze to help guide you along. There will not be a cursor indicating your position along the maze.

Procedure: Before each trial you will be given a blank screen with a circle in the middle. There are two cursors representing your current location. The large yellow cursor is a forward projection of your location. The small white cursor is a right projection of your location. You need to center both of these cursors in the circle before you start. This is to make sure you start at the same spot for every trial.

You hold the stylus in your hand as you would a pencil and rest your forearm in the arm rest. Once you have aligned the cursor you can press any key to start.

A red maze will appear. There will also be a green starting block and a black finishing block. Move the Stylus forward until you feel the front wall. To start, move to the left and touch the green block gently. The block will turn light green. Once you let go, the timer will start and While you are going through the maze, please stay in contact with the front surface. You can use the other wall surfaces to guide you through the maze. Once you touch the black finishing block you will be finished with that trial. There will not be a cursor to show you your exact location. Use the feel of the maze to guide you through.

There are a total of 45 trials. You will be asked to rank several of the trials on a scale of 1 to 5 on ease of completing the maze after the 5th trial.
1 = very hard
2 = hard

3 = not too hard, not too easy
4 = easy
5 = very easy

Experiment 4:

Objective: To complete the maze as quickly as possible. Follow the path through the maze. You may touch the walls of the maze, but try not to pass through the walls. There will be a visual cursor indicating your position along the maze. You will not have any force feedback from the walls of the maze.

Procedure: Before each trial you will be given a blank screen with a circle in the middle. There are two cursors representing your current location. The large yellow cursor is a forward projection of your location. The small white cursor is a right projection of your location. You need to center both of these cursors in the circle before you start. This is to make sure you start at the same spot for every trial.

You hold the stylus in your hand as you would a pencil and rest your forearm in the arm rest. Once you have aligned the cursor you can press any key to start.

A red maze will appear. There will also be a green starting block and a black finishing block. Move the Stylus forward until you feel the front wall. To start, move to the left and touch the green block gently. The block will turn light green. Once you let go, the timer will start and While you are going through the maze, please stay in contact with the front surface. Once you touch the black finishing block you will be finished with that trial. There will be a cursor to show you your exact location It is OK to visually touch the walls of the maze, but Try not to pass through the walls of the maze.

There are a total of 45 trials. You will be asked to rank several of the trials on a scale of 1 to 5 on ease of completing the maze after the 5th trial.
1 = very hard
2 = hard
3 = not too hard, not too easy
4 = easy
5 = very easy

Experiment 5 & 6

Objective: To complete the maze as accurately as possible without touching the walls.

Procedure: Before each trial you will be given a blank screen with a circle in the middle. There are two cursors representing your current location. The large yellow cursor is a forward projection of your location. The small white cursor is a right projection of your location. You need to center both of these cursors in the circle before you start. This is to make sure you start at the same spot for every trial.

You hold the stylus in your hand as you would a pencil and rest your forearm in the arm rest. Once you have aligned the cursor you can press any key to start.

A red maze will appear. There will also be a green starting block and a black finishing block. Move the Stylus forward until you feel the front wall. To start, move to the left and touch the green block gently. The block will turn light green. Once you let go, the experiment will start and While you are going through the maze, the only surface you should touch is the front surface(floor of the maze). Try to minimize contact with any other surface. Once you touch the black finishing block you will be finished with that trial.

There are a total of 62 trials. You will be asked to rank several of the trials on a scale of 1 to 5 on ease of completing the maze half way through the session.
1 = very hard
2 = hard
3 = not too hard, not too easy
4 = easy
5 = very easy

Experiment 7:

Objective: To complete the maze as accurately as possible without passing through the walls. You can use the walls as a guide, but be careful not to apply too much force, since it is possible to pass through the walls.

Procedure: Before each trial you will be given a blank screen with a circle in the middle. There are two cursors representing your current location. The large yellow cursor is a forward projection of your location. The small white cursor is a right projection of your location. You need to center both of these cursors in the circle before you start. This is to make sure you start at the same spot for every trial.

You hold the stylus in your hand as you would a pencil and rest your forearm in the arm rest. Once you have aligned the cursor you can press any key to start.

A colored maze will appear. There will also be a green starting block and a black finishing block. Move the Stylus forward until you feel the front wall. To start, move to the left and touch the green block gently. The block will turn light green. Once you let go, the experiment will start. While you are going through the maze, stay in contact the front surface(floor of the maze). Once you touch the black finishing block you will be finished with that trial.

There are four different types of maze interfaces. Each of the 4 interfaces are color coded to help you distinguish them.
In some mazes you will control your location by where you move,
in other mazes you will control your location by the force you apply.
In some mazes your motion will change the location of the cursor,
in other mazes you motion will change the location of the background.

There are a total of 72 trials. You will be asked to rank several
of the trials on a scale of 1 to 5 on ease of completing the maze.
1 = very hard

2 = hard
3 = not too hard, not too easy
4 = easy
5 = very easy

Appendix B

Boxplots

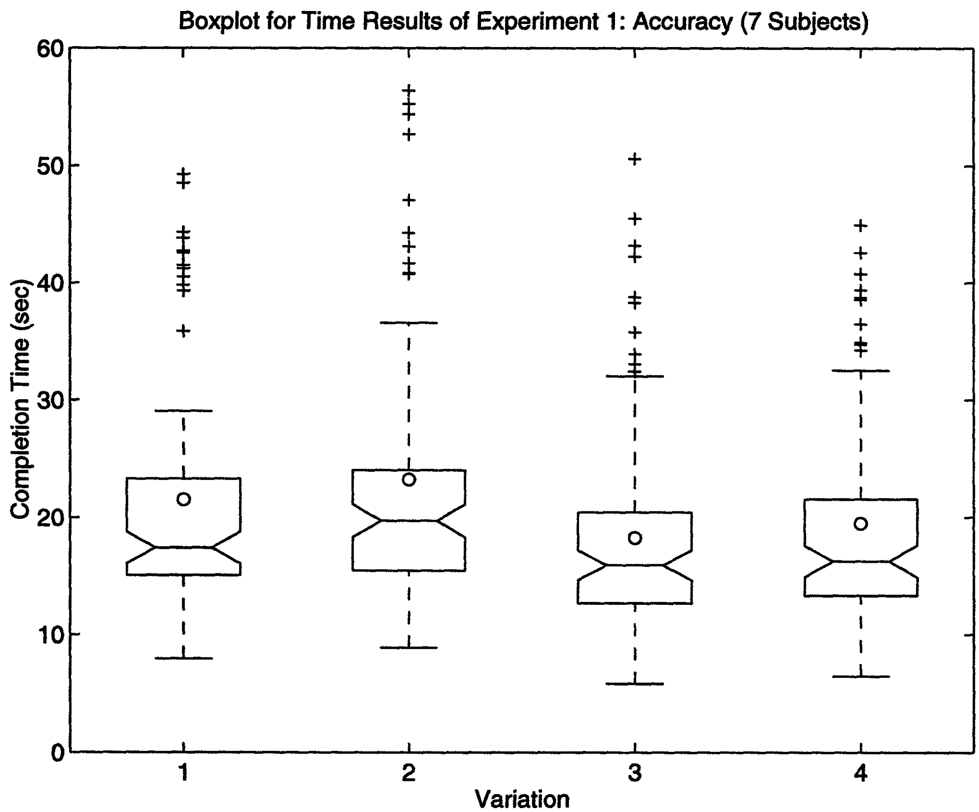


Figure B-1: Boxplot of the time results for Experiment 1: Accuracy. Variation 1: mean = 21.5 ± 1.3, median = 17.4 . Variation 2: mean = 23.2 ± 1.5, median = 19.7 . Variation 3: mean = 18.2 ± 1.0, median = 15.9. Variation 4: mean = 19.5 ± 1.1, median = 16.3. (sec)

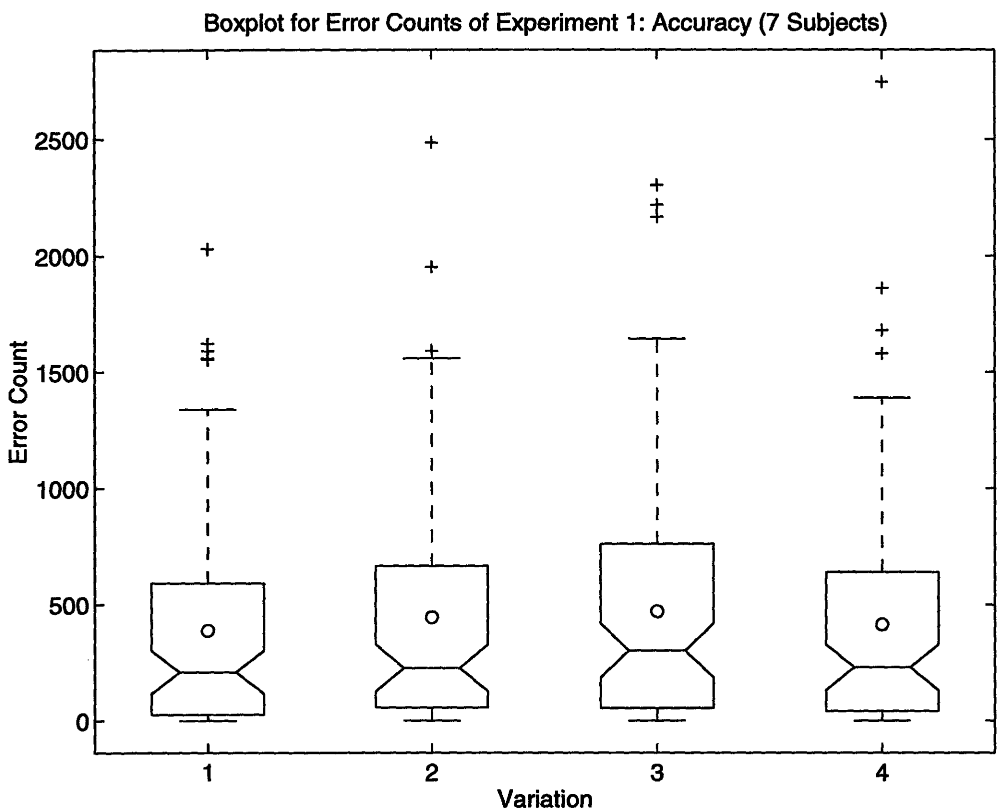


Figure B-2: Boxplot of the error results for Experiment 1: Accuracy. Variation 1: mean = 389 ± 50, median = 209. Variation 2: mean = 445 ± 54, median = 227. Variation 3: mean = 470 ± 56, median = 302 . Variation 4: mean = 414 ± 52, median = 230. (counts)

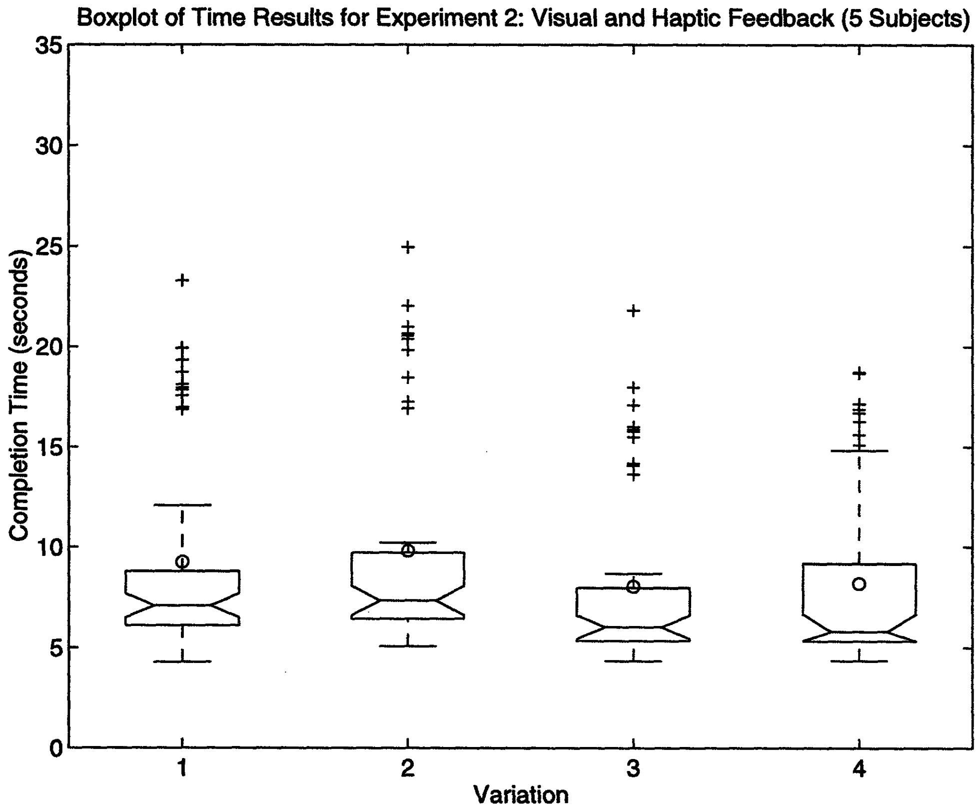


Figure B-3: Boxplot of the time results for Experiment 2: Speed, Visual and Haptic Feedback. Variation 1: mean = 9.3 ± 0.7, median = 7.1. Variation 2: mean = 9.8 ± 0.8, median = 7.3. Variation 3: mean = 8.0 ± 0.6, median = 6.0. Variation 4: mean = 8.2 ± 0.6, median =5.8. (sec)

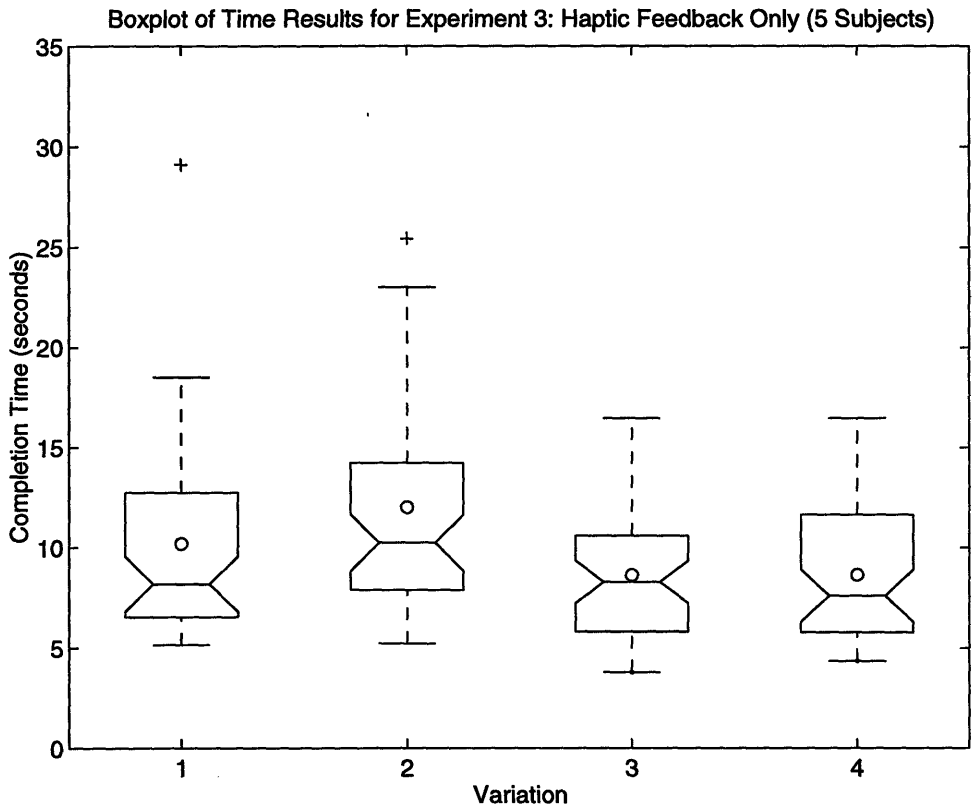


Figure B-4: Boxplot of the time results for Experiment 3: Speed, Haptic Feedback Only. Variation 1: mean = 10.2 ± 0.7, median = 8.2. Variation 2: mean = 12.0 ± 0.9, median =10.2. Variation 3: mean = 8.6 ± 0.4, median = 8.3. Variation 4: mean = 8.6 ± 0.5, median = 7.6. (sec)

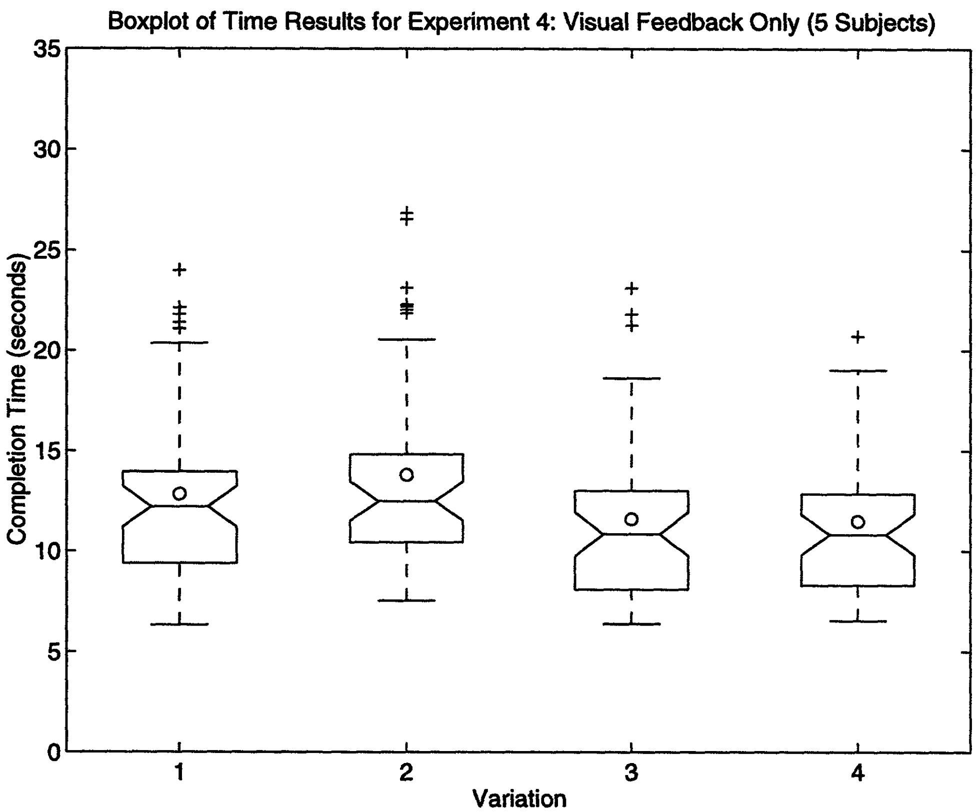


Figure B-5: Boxplot of the time results for Experiment 4: Speed, Visual Feedback Only. Variation 1: mean = 12.9 ± 0.6, median = 12.2 . Variation 2: mean = 13.8 ± 0.7, median =12.5. Variation 3: mean = 11.6 ± 0.6, median = 10.9. Variation 4: mean = 11.5 ± 0.5, median = 10.8. (sec)

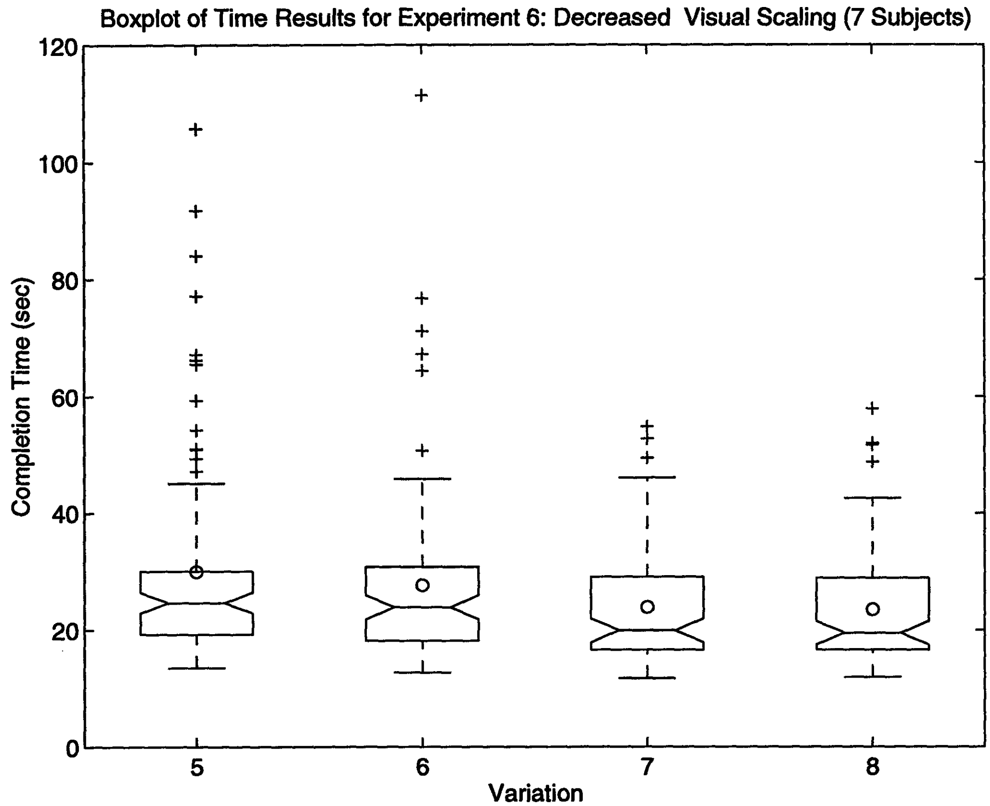


Figure B-6: Boxplot of the time results for Experiment 6: Decreased Visual Scaling. Variation 5 ("Small"): mean = 30 ± 1.9, median = 24.7. Variation 6 ("Medium"): mean = 27.7 ± 1.6, median = 23.9. Variation 7 ("Large"): mean = 23.9 ± 1.1, median = 19.9. Variation 8 ("Ex-large"): mean = 23.5 ± 1.0, median = 19.5. (sec)

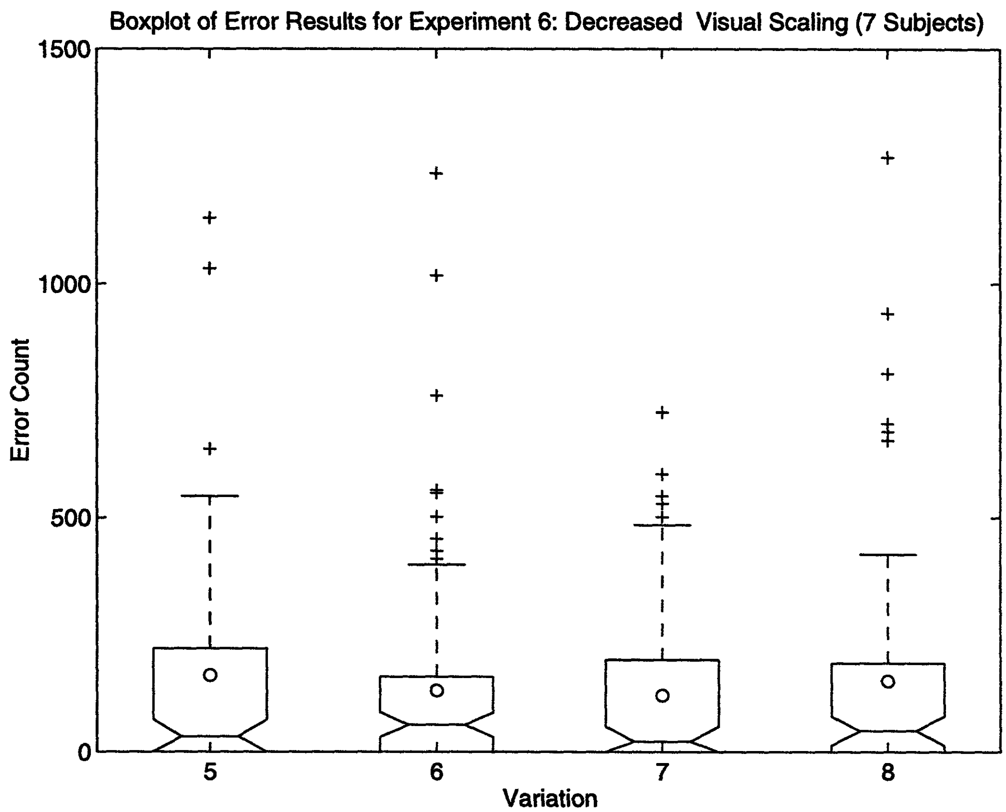


Figure B-7: Boxplot of the error results for Experiment 6: Decreased Visual Scaling. Variation 5 ("Small"): mean = 164 ± 34, median = 33. Variation 6 ("Medium"): mean = 131 ± 22, median = 58. Variation 7 ("Large"): mean = 121 ± 18, median = 22. Variation 8 ("Ex-large"): mean = 151 ± 29, median = 45. (counts)

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