

**COMPARING AND CONTRASTING MANUAL
DIRECT TOUCH INTERACTION WITH
TANGIBLE USER INTERFACES FOR
MAPPING APPLICATIONS**

BY

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ABSTRACT

COMPARING AND CONTRASTING MANUAL DIRECT TOUCH INTERACTION WITH TANGIBLE USER INTERFACES FOR MAPPING APPLICATIONS

by

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Multi-touch interfaces are growing in popularity for many forms of computing devices, including mobile devices, as well as personal and shared workstations. There has been limited exploration into the use of tangible user interfaces in conjunction with multi-touch displays for extracting data from geocoded data. Specifically, it is not known if tangible user interfaces are faster, easier or more intuitive to use than existing touch based controls. We hypothesize that tangible user interfaces will be faster, more satisfying and more desirable than touch based controls for extracting data from geocoded data. We set out to explore one tangible user interface and two touch based interfaces as inputs to a new mapping application.

CHAPTER 1

INTRODUCTION

1.1 Exploring Geocoded Data with a Multi-Touch System: Problem Statement

Multi-touch interfaces are growing in popularity for many forms of computing devices, including mobile devices, as well as personal and shared workstations. Many new systems include sample mapping software powered by technologies like Microsoft's Bing Maps [21], Google Maps [13] and Open Street Map [19]. As multi-touch enabled computing devices such as table top computers and cellphones gain traction in the market, new applications are developed taking advantage of new multi-touch based features. One common area for application development focuses on data that can be linked to a set of geographic coordinates and displayed on maps, also known as geocoded data. In some cases, when using geocoded data, another dimension may be added to allow users to gather more data visually. Displaying weather patterns or other weather data is an example of multiple dimensions on one screen. For most touch interfaces or traditional desktops, application requiring user input usually consists of a display area and a separate control area. The Weather Channel® Application for Apple's iPhone® [12] is a good example of separate control and viewing areas. As seen in Figure 1-1, there is the display area with the map and the geocoded data, below which are the slider and control buttons. While it may be easy to use based on prior experience, applications with separate navigation areas take up screen space that could be used to display more information to the end user. Additionally,

many new devices allow tracking of objects other than fingers, which could be used for multi-touch of interaction, freeing more screen space for other purposes or more sophisticated interfaces that can be reloaded on the screen.



Figure 1-1: A screen shot of the Weather Channel Application for the iPhone [15]

In recent years, applications have started to display more data while maintaining the same or smaller screen space. Very few new interfaces have been developed in the last few years for minimizing or removing the control portion of touch displays. Also, with the improvements to touch displays, few interfaces have been developed to take advantage of object tracking. Even fewer, if any, have been used for interfaces to geocoded data.

The growing collection of geocoded data being displayed on touch based displays would greatly benefit from more usable screen real estate to provide more information at one time. One possible way to reclaim some of the screen space

would be to use a tangible user interface. A tangible user interface is some object which could use little to no permanent screen space, and provide an interface to a computer through physical manipulation.

1.2 Goals

Our primary goal was to analyze the use of tangible user interfaces for the exploration of geocoded and time-coded data. Our first goal was to create a touch based application, which could be used to compare existing touch based methods for exploring data using a map to two new interfaces. Our second goal was to examine three possible methods of measuring the cognitive load of a subject who was using a touch based interface.

1.3 Hypotheses

Our first hypothesis was that users will be able to complete a data extraction task faster when using an interface that has a tangible component than a strictly touch based user interface.

Our second hypothesis was that users will be more satisfied to use a tangible user interface when they are given the option to use either a strictly touch based interface or a tangible and touch based interface.

Our third hypothesis was that users will be less cognitively loaded when interacting with a tangible user interface as compared to a touch only interface.

1.4 Approach

We have divided our research into four phases: (1) development of two new interfaces, (2) development of the testing application(s), (3) experimentation with human subjects and (4) analysis of the resulting data.

1.4.1 Development of two new interfaces

The first interface to be developed was a tangible user interface that allows users to have part of the user input controlled by the motion of a physical object. For

the experiments covered later, users interact with a standard hockey puck. A hockey puck controlled the fine movement, while the coarse adjustment will be done with a slider type interface. Going forward, the coarse motion section of the new interfaces will be referred to as the “Scrubber”.

The second interface was dubbed the “Virtual Puck” interface. The primary purpose of the Virtual Puck interface was to have an input method to compare the new interfaces to. The second interface consisted of the same scrubber component as the first interface, but rather than the puck, a circle was used. Similar to the first interface’s interaction, the grey circle allows the user to place their finger on the input device and rotate it only using only direct touch. The “Virtual Puck” interface was designed fall between the “Physical Puck” and the control.

The control for our user studies was an existing interface within the Application Programming Interfaces or APIs of the Microsoft Surface known as the SurfaceSlider. The SurfaceSlider component was very similar to a slider in most common computer applications, such as word processors or Internet browsers.

1.4.2 Development of the testing application(s)

During the development and testing phase, two applications were created to test two different aspects of the new interfaces. The first application was a number finding program, which was used to try to measure the cognitive load of the user while interacting with the device. The second application was designed to test the ability of users to extract data from a collection of time-coded and geocoded data. The major element of the second application was a simulated mapping environment using a mocked up grid style street pattern on which “vehicles” could move freely. One constant across both applications was the Microsoft Surface, the platform on which both applications run.

1.4.3 Experiment with Human Subjects

There were two different experiments that were run with human subjects. The first experiment was used to test both the users preference of interface, as well as the speed of their completion of given tasks. For our first study, users interacted with the application that used a mocked up map as the display. Subjects were given three different sections of questions, one corresponding to each of the two new interfaces and another for the control interface. At the start of each section of questions, the user was instructed on the proper usage for each interface. Following the instruction section, a set of practice questions were given to let the user practice the interface before beginning the experiment. Finally, the user were given a set of questions that they are asked to complete as fast as possible while also getting the correct answer. To ensure that the learning effect was accounted for, the presentation order for the interfaces were counterbalanced. Following each section of the experiment, users were asked to complete a NASA-TLX assessment. In addition to the data gathered from the users interaction, video footage captured the entire experiment for possible review after the experiment was over. The video footage only started after the consent forms were completed. Also, in an attempt to measure the relative cognitive load of the user, physiological measurement devices were connected to gather heart rate as well as skin conductance. Finally, in order to gather subjective and demographic data, questionnaires were administered prior to and after the experiment.

For the second experiment, a similar setup was maintained. The differences were in the application used and the method of measuring cognitive load. The application for the second experiment consisted of an external monitor displaying two numbers, one on top of the other. The top number was a number that the user was attempting to locate in an ordered list of numbers from 1 to 10000. The bottom number was used to indicate the number that the user currently had selected. To measure cognitive

load, subjects were not be connected to physiological measurement devices, but an eye tracker was used to measure the diameter of the subjects' pupil.

1.4.4 Analysis of the Resulting Data

Both quantitative and qualitative methods were used to analyze the data gathered. The qualitative data from Likert scales on the questionnaires were analyzed to locate possible trends concerning the subjects' familiarity with touch based interfaces as well as tangible user interfaces. The quantitative analysis was used to compare timing data for many different activities within each user interaction.

CHAPTER 2

BACKGROUND

2.1 Touch Based Computing Devices

Many devices have been introduced which utilize touch as a method of interaction. From touch pads on almost all laptops to large touch screens the size of walls [24], touch is being used increasingly as a primary method of interaction with some computing devices. Another common use of touch interaction appears in many types of smart phones such as Apple's iPhone® [12], Google's Android [14] and Microsoft's Windows® Phone [23] to name a few. Before 1984 [3], computer based touch interfaces were only capable of responding to a single touch at a time. In 1984, researchers began to experiment with the use of multi-touch tracking, creating a need for computer software that could understand more than one touch at a time [4].

When research and development of touch and contact based interface systems began, most systems implemented their own software. As more focus was placed on touch input and object tracking, software [9] and hardware [22] packages emerged to simplify development. Echtler et al. reviewed many of the existing software and hardware packages available in 2008 and developed a system architecture which is commonly seen in past and present systems [4]. Rather than highlighting strengths and weaknesses of each individual implementation, the authors distilled the major components of many systems into a layered architecture outlined in Figure 2-1.

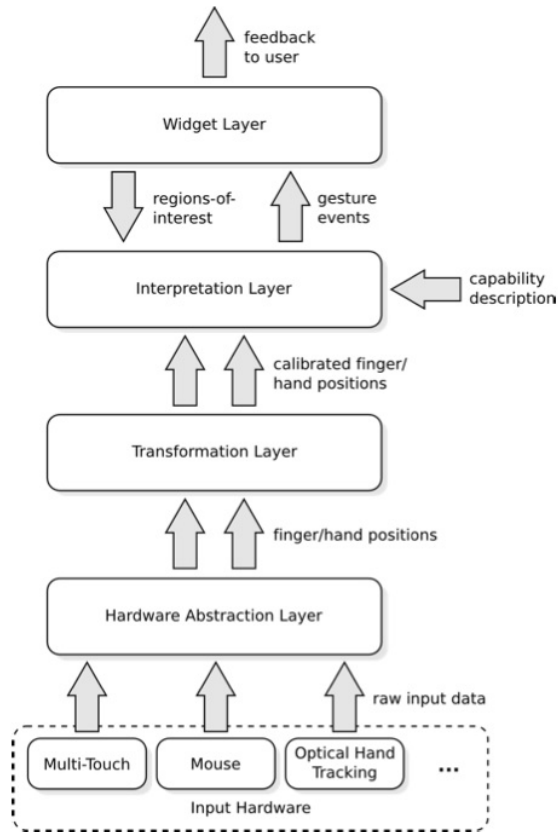


Figure 2-1: Layered software architecture outlined by Echtler et al. [4] © 2008 Association for Computing Machinery, Inc. Reprinted by permission.

Expanding on the layered software architecture, Echtler et al. encouraged further development to focus on only one particular layer in the stack at a time, while only making small changes to other portions of the stack when necessary. When only creating one layer, the developers can allow other existing technology to take advantage of new enhancements via API's or hardware interfaces. Although not all of the current technologies adhere to the layered structure, many loosely follow its design pattern. For example, the implementation of the Microsoft Surface abstracts all but the widget layer and some of the interpolation layer. By exposing the widget and interpolation layers, Microsoft allows

users to develop applications that are portable between the current Microsoft Surface ® and the new Microsoft Surface ® Version 2.0.

Another implementation of the multi-touch stack can be seen with the Community Core Vision (CCV) project run by the Natural User Interface group [8]. CCV is a collection of applications which can closely map to each of the different layers of the multi-touch software architecture. First, the package has a set of software drivers that can be used to communicate with user provided hardware, such as cameras or resistive touch panels, represented by the Hardware Abstraction Layer (HAL). From

the HAL, data is then processed and turned into a data abstraction for each point of contact. In the most common case, CCV uses image processing to generate the contact information, which is an example of the Transformation Layer. Once the contact information has been generated, it is passed to the CCV's Application Layer. The Interpolation and Widget layers are where CCV, Microsoft Surface and most other implementations differ by incorporating both layers into a single Application Layer. In both cases, the Interpolation and Widget layers are contained within each individual application, while still maintaining some separation.

2.2 Touch Interactions vs. Mouse Interactions

During the development of many touch based interactions, comparisons were made between the new interfaces and traditional mouse based interfaces. One example by Sears et al. focused on target selection with touch based interfaces and a mouse interface [25]. In Sears et al.'s study, selection times for targets of different sizes were tested for two touch based input methods and a standard mouse device. The two touch interfaces consisted of a stabilized and non-stabilized input method. The primary difference between these two interfaces was the behavior when the user's finger was in contact with the screen. For the non-stabilized method, when the point of contact first touched the screen, the location was passed to the application. For the stabilized method, once contact had been made with the screen the user had the ability to adjust their selection providing finer motion control.

Along with measuring the timing of user selections, the authors collected error rates and user satisfaction ratings. The results of their study can be seen in the following tables and charts.

First, Table 2.1 and Figure 2-2 show the timing results of Sears et al. user study. The data shows a trend, as Sears et al. hypothesised, that the larger the target

	Target Size (Pixels per side)			
	32	16	4	1
Mouse	3.13 (1.28)	3.47* (1.60)	4.97 (1.98)	6.08* (1.87)
Stabilized Touchscreen	1.83 (0.37)	1.98 (0.33)	4.27 (1.27)	11.78 (4.42)
Non-Stabilized Touchscreen	1.86 (0.45)	1.93 (0.47)	4.57 (1.65)	12.28 (4.95)

Table 2.1: Mean selection time (in seconds) per target (standard deviation in parentheses). (* $p < 0.05$) from Sears et al. [25]. Reprinted from International Journal of Man-Machine Studies, 34 /4, Sears, Shneiderman, High precision touchscreens: design strategies and comparisons with a mouse, 593-613, Copyright (1991), with permission from Elsevier

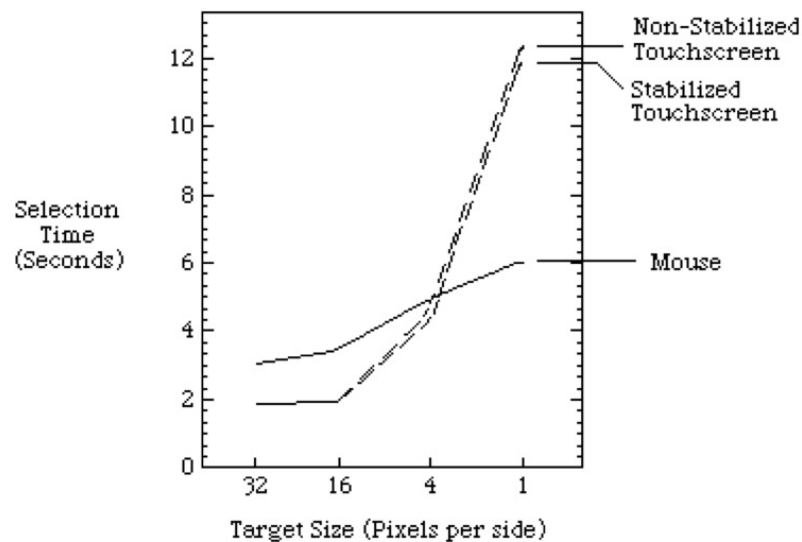


Figure 2-2: Selection time for four target sizes and three selection methods from Sears et al. [25]. Reprinted from International Journal of Man-Machine Studies, 34 /4, Sears, Shneiderman, High precision touchscreens: design strategies and comparisons with a mouse, 593-613, Copyright (1991), with permission from Elsevier

the faster a user was able to make a selection. There was a significant difference ($p < 0.05$) between the mouse selection times and the two touch interfaces for targets with 16 and 1 pixel(s) per side. Additionally, the results did not show any significant

difference in selection time between stabilized and non-stabilized touchscreen input methods.

The error results are shown in Table 2.2 and Figure 2-3. Also as the author hypothesised, the error rate for the mouse was lower than both touchscreen methods and that the non-stabilized touchscreen was more error prone than the stabilized version. Both error results were significant ($p < 0.05$) for the non-stabilized touchscreen for targets with 4 pixels per side and both touch inputs for 1 pixel per side.

	Target Size (Pixels per side)			
	32	16	4	1
Mouse	0.08 (0.15)	0.06 (0.12)	0.08 (0.18)	0.50 (0.68)
Stabilized Touchscreen	0.03 (0.06)	0.05 (0.10)	0.35 (0.58)	1.53* (1.08)
Non-Stabilized Touchscreen	0.02 (0.06)	0.06 (0.15)	0.77* (0.60)	4.38* (0.62)

Table 2.2: Mean number of errors per target (standard deviation in parentheses). (* $p < 0.05$) from Sears et al. [25]. Reprinted from International Journal of Man-Machine Studies, 34 /4, Sears, Shneiderman, High precision touchscreens: design strategies and comparisons with a mouse, 593-613, Copyright (1991), with permission from Elsevier

	Mouse	Stabilized Touchscreen	Non-Stabilized Touchscreen
Mean User Preference Rating	7.5 (1.7)	6.7 (1.9)	1.9* (1.5)

Table 2.3: Mean user preference ratings for three selection devices (standard deviation in parentheses). (* $p < 0.05$) from Sears et al. [25]. Reprinted from International Journal of Man-Machine Studies, 34 /4, Sears, Shneiderman, High precision touchscreens: design strategies and comparisons with a mouse, 593-613, Copyright (1991), with permission from Elsevier

Finally, the subjective data shown in Figure 2-3 shows a trend that the subjects preferred the mouse over the stabilized touch screen and significantly ($p < 0.05$) preferred either the mouse or stabilized touchscreen over the non-stabilized touch screen.

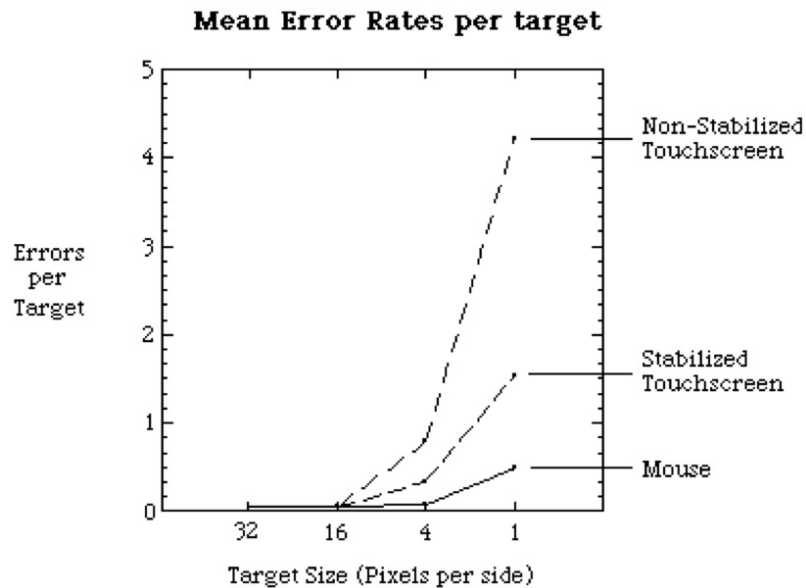


Figure 2-3: Error rates for four target sizes and three selection methods from Sears et al. [25]. Reprinted from International Journal of Man-Machine Studies, 34 /4, Sears, Shneiderman, High precision touchscreens: design strategies and comparisons with a mouse, 593-613, Copyright (1991), with permission from Elsevier

In a similar study, Forlines et al. investigated user interaction comparing touch screen input with mouse input for larger targets while taking distance into account [7]. The results from Forlines et al.'s study agree with Sears et al.'s study. Having learned from the work by Sears et al., our experiments used targets 16 pixels per side or greater. Forlines et al. also reviewed the error rate with relation to the distance from the user. When the target was within 300 pixels of the user, the error rate was significantly less than the same distance with the mouse. When reaching 400 pixels and beyond, the error rates of touch increased faster in comparison to the mouse error rates.

2.3 Errors

Many studies have mentioned the existence of errors due to interfaces. One of the most common occurrences involved properties of using a finger as an input device. Many authors [7, 6, 17, 18, 25, 26, 28] have noted that the finger can be a very inaccurate method of selection, commonly referred to as the “Fat Finger” problem. The primary cause of the fat finger problem is the surface area that is in contact with the input device during interactions. The “Fat Finger” problem accounts for a large percentage of selection errors for small targets [6, 25, 28].

A difficulty related to the “Fat Finger” problem was also presented by Forlines et al. [6]. A similar issue was that users had difficulty locating targets that were close to the subject. There are several possible explanations for users having difficulty finding targets close to them ranging from occlusion by the hand or arm to the ability of the user to see more context the further they are looking. Either of these explanations would help support the claim of difficulty locating targets close to the user and should be taken into account when designing interfaces.

Another common source of error when trying to select targets on a touch-screen based device is what is termed “Lift Off Error” [25]. Lift off error is a result of a user’s finger being removed from the touch-screen and in the process either moving his/her finger or not having the center of the user’s finger be the last point in contact with the display. When lift off error occurs, the system processing touches may interpret the finger being lifted off the display as a movement before it is able to process the contact removal. Lift off errors usually results in small objects not exhibiting the expected behavior, or in the case of movement, objects not being in the desired location after the interaction is completed.

2.4 User Interface Design

2.4.1 Design Suggestions to Facilitate Use

When making good user interfaces, there are a number of factors that should be taken into consideration. One aspect of interface design, that can affect an interface in terms of usefulness and acceptance, is the ability for users to identify acceptable gestures just by exploring the interface [28]. An example of gestures that can be discovered by exploration would be pinching to zoom on many smart phones and tablet computers. If users are able to learn a majority of the gesture vocabulary without prompting, they feel a sense of accomplishment and are more willing to experiment with new interactions.

Another important aspect to pay attention to is the size of all components in the interface in relation to the overall screen size, the size of the pixels (or dot pitch) and the size of a finger. When dealing with large screens, subjects are more likely to have difficulty locating targets that are close to them with a similar size to their finger [6]. Also the users may experience difficulty if the targets are far away and are very small or otherwise difficult to see.

2.4.2 Design Considerations for Decreasing User Fatigue

Physical strain caused by using an interface is very important to be aware of, especially when dealing with interfaces that are intended for extended periods of use such as keyboards or pointing devices. Forlines et al. noted that with direct touch, while the users were faster and more satisfied with the interactions, arm fatigue was much more common [6]. In contrast, when using relative pointing, the users were less satisfied with performance, but also experienced less fatigue. Although Forlines et al. work was done with large up-right screens, it suggests that restricting the reaching required for the interaction may decrease strain to the user.

Wang et al. reviewed an informal user study in regards to their multi-touch wall [28]. They noted that users experienced fatigue in their arms more quickly when interacting with the vertical plane. Also observed in Wang et al. study was how many hands the users had in contact with the interface at the same time. The researchers mentioned that a majority of the users preferred to use one hand as much as possible, only relying on their second hand when needed. In addition to the vertical devices, Forlines et al. went on to explore how horizontal devices could also induce fatigue if the subject had to reach a long distance, or interact with the input device for extended periods [7].

2.4.3 Design Considerations for Increasing User Satisfaction

When trying to design user interfaces, user satisfaction should be one of the most important factors to consider. If the users are not able to understand the interactions or get confused while using the interface, they will lose interest or become frustrated. Wang et al. identified two elements for good interface design while working with their vertical wall touch screen [28]. First, users avoid interfaces that require a lot of effort to use. An example of an interface requiring a lot of effort is moving objects on a screen a long distance. To avoid long distance movements, another group of researchers have developed relative pointing methods such as the HybridPointing interface [6]. The second element the authors listed was the ability for users to identify the applicable gestures for each interface. Identifying applicable gestures could be based off of previous experience with computer interface technologies such as mice and keyboards or previous experience with real world objects such as building blocks and writing utensils.

Shneiderman performed extensive research into user interface design for both touch based and traditional computer systems [26]. Following the user studies, re-

sults were distilled from both the subjective and recorded data. The following list is a collection of positive reports from Shneiderman's subjects:

- The mystery of a new interface is exciting for new users.
- It is fun to learn how to use intuitive interfaces.
- Many users are excited to show off new and easy to use interfaces to novice users.
- If interfaces have advanced features, they should be separated from the basic set and not required for casual use.
- After users have reached a competency with the basic features they are eager to learn the more complex features.

Shneiderman also compiled a list of requirements for a well designed interface. First, continuous representation of the objects and/or action of interest helps the user by reducing the information they have to remember while working. Interactions should be based on buttons and physical actions rather than complicated syntax. Finally, the interface should allow rapid interactions which are also easily reversible, reducing the impact of a mistake or missing a target.

2.5 Tangible User Interfaces

One major advantage of the Microsoft Surface over other systems is the ability to incorporate tangible objects into its applications very easily. In addition to small user studies done with the Microsoft Surface, previous research has been done focusing on tangible objects to aid touch based interactions.

One example of tangible interfaces with touch input was explored by Maher et al. [18]. During Maher et al.'s study, users were asked to design a layout for a

room. Recordings of the experiment were reviewed and all actions were categorized using a system the researchers created. After analyzing the data, the conclusion was drawn that users would experiment more with layouts when using a tangible interface compared to a touch screen. Users also reported that they preferred using the tangible interface in place of the touch method.

Another tangible user interface reviewed was the HybridPoint by Forlines et al. [6]. The HybridPoint interface was designed to reduce the fatigue of the user and decrease the time required for interactions. The name of Forlines et al.'s interface was derived from its two input methods. For close targets users could have used direct touch where the tip of the input device was the selection point. The other method was relative touch, which could be used like a mouse to move to the extent of the user's reach and then picked up and moved again to reach further away. Picking up the device and moving it is very similar to using a mouse to move across a large screen. One important finding from the HybridPoint study was for screen sizes less than 1892 pixels on any side direct touch resulted in a faster completion time and a less frustrated user. The screen size was important to note for the Microsoft Surface, which has a maximum resolution of 1024 by 768 pixels.

Finally, the Haptic Tabletop Puck by Marquardt et al. was explored [20]. The Haptic Tabletop Puck used a wooden block as an input and output device for a touch based surface. When users positioned the device over a point on the screen, an actuator would change the height of a dowel in the block. One use case for the Haptic Tabletop Puck given in the paper was a topographical map exploration program. When the user selected a point on a terrain, the dowel would be raised to a representation of the height on the map. Users could then drag the puck across the map and the dowel height would change with respect to the new location. During the development of Marquardt et al.'s puck interface the size of the device (69x69x40

mm) was deemed acceptable by a pilot study. The Haptic Tabletop Puck’s size was similar in size to a hockey puck (76x25 mm) which was explored in the user studies presented later.

2.6 User Interfaces

The following sections are short reviews of two different user interfaces which which have been considered for possible implementation in the user studies to follow.

2.6.1 Alpha Slider

The Alpha Slider by Ahlberg et al. was the starting point for the two user studies that follow [2]. The authors had implemented new slider based interfaces in a Graphical User Interface (GUI) for a traditional workstation. In order to test these new input methods, a study was designed to have users select specific pieces of data from a large data set, in Ahlberg et al.’s case movie titles.

2.6.2 Data Visualization Slider

The Data Visualization Slider explored by Eick was a promising method of displaying the distribution information for data in a given set [5]. The addition of a distribution of the full data set was not implemented due to the uniform distribution of the data through the entire dataset used for each experiment. If the interfaces explored later are used for any applications using non-uniform data distributions, the ideas presented in Eick’s work may decrease the selection time if the data distribution is not uniform.

2.7 Training of Users

As mentioned before, one of the user studies performed was modeled after the work by Ahlberg et al. [2]. The authors noted that an important part of obtaining

justifiable results was giving the subjects practice with all interfaces, new or old. Ahlberg et al.’s suggestion was also supported by Sears et al. for their direct touch experiment [25]. Both of the papers noted that users who had more experience with the interface were better at the interaction overall. Both Ahlberg et al. and Sears et al. also note that even if an interface was new, a short exposure to a new interface with the ability to ask questions or get feedback could improve performance.

2.8 Estimating Cognitive Load

The cognitive load of a user cannot be quantified as a single number, but there has been work which suggests it is possible to estimate relative cognitive load of a user by comparing different measures for different tasks. Ikehara et al. cover several possible methods for estimating the cognitive load of a user by physiological sensors [11]. Our lab had the ability to measure four of these methods: pupil size, blink rate, skin conductivity and heart rate. All four methods could be used to estimate real time cognitive load either at the time of the experiment or when compared to recorded data. Ikehara et al. also mention that subjective rating scales can also provide a measure of cognitive load. While not real time, subjective rating scales can be used to estimate the cognitive load for a collection of tasks. One example of subjective rating scales is the NASA-TLX assessment [10]. NASA-TLX uses a series of questions and weighting to determine rank and weight of user perceptions. At the end of the assessment a single number is given as an estimate of their cognitive load for a task.

CHAPTER 3

APPROACH

3.1 Phases of the Research

As stated in the introduction, the research covered in the following chapters explore the benefits of using tangible user interfaces when reviewing time-coded and geocoded data on a touch based display. Our primary goal was to explore any possible advantages or disadvantages when using tangible user interfaces in conjunction with mapping technologies on a touch based display. The research was divided into four phases:

1. Development of two new interfaces
2. Development of the testing applications
3. Experiment with human subjects, and
4. Analysis of the resulting data.

3.2 Development of Two New Interfaces

3.2.1 User Interface Control Requirements

Developing a user interface that was appealing to most users was a difficult task. To do so, many aspects were taken into account. Section 2.4 discussed various attributes of both good and bad interface designs. The following sections outline the important attributes that were considered when designing the user new interfaces below.

3.2.1.1 Coarse and Fine Motion Control

Smith et al. noted that user interfaces designed to interact with data sets should have three different speeds of navigation [27]. The three speeds as defined in Smith et al.’s paper are listed in Table 3.1. To reduce the complexity of the interfaces used for both experiments, only two different control methods were implemented for each interface while ensuring all three movement types were available.

Table 3.1: Movement types for user interfaces that explore large data sets effectively.[27]

Movement Type	Description
Gross Movement	Very large jumps through the list
Moderate Movement	Control over position, achieved through a closed-loop feedback process
Fine Movement	Movement by single items

First, the coarse motion control method for all interfaces, including the control, was implemented using a “scrubber” type interface. Scrubber interfaces are common in many computer applications. Examples of scrubbers include scroll bars and some web elements such as YouTube’s® video time controls. Scrubbers have the ability to jump long distances, as required by gross movement and the ability to scroll at a slower rate as required by moderate movement.

The second method of motion was referred to as fine motion control. For both of our experiments, fine motion incorporated part of moderate movement and all of fine movement. For the fine motion control, users have the ability to move a single data point in either direction, fulfilling the fine movement requirement and more than one data point to fulfill the requirement of moderate movement. The interface sections below will discuss how both coarse and fine motion control were implemented in more detail.

3.2.2 Control Interface

The control interface was created with the default Microsoft Surface “SurfaceSlider” with one default “SurfaceButton” control to its the left and right. A screen shot of control interface can be seen in Figure 3-1. In the center of the figure, the horizontal line with the circle was the “Scrubber” portion of the control interface. As described in Section 3.2.1.1, the scrubber interface was implemented in a way that users can navigate data quickly or at a moderate pace depending on the speed of the users finger. For the fine motion control, the buttons on either side of the scrubber were used. When users tapped either button, the data selection would move one point up or down when the right or left were pressed respectively. If a user held down either button, the interface would begin to iterate through the data points at an increasing rate until a maximum of 20 data points per second. The fast scrolling feature allowed users to get achieve moderate movement in addition to the fine movement from tapping.



Figure 3-1: A screen shot of the control user interface.

Shneiderman’s guidelines were also considered for the control interface [26]. First, user interfaces should continually represent its state. State was displayed by using the circle on the horizontal line of the scrubber. As the user traversed through the data, the circle would move to show the current location within the data set. Second, all interactions for the control interface were directly related to the elements of the interface. The users did not have to perform any complex gestures in order to manipulate the data. Finally, every change made to the interface was easily reversible.

For example, if the user had scrubbed too far through the data, they were able to easily move their finger backwards. The fine motion control portion of the control interface was also reversible, if the subjects were pressing the buttons and passed the desired point in the data set, pressing the opposite button would move them in the other direction.

3.2.3 Physical Puck Interface

The physical puck interface was the result of an iterative process to develop a new method for interacting with sequential data sets. The primary purpose of the physical puck interface was to include a tangible object as part of the user interface. Most user interfaces for interacting with sequential data sets maintain some state information in its presentation. For example the control interface displayed its state by moving the circle on the slider section of the interface. In some tangible interfaces, like switches and many knobs, state information is stored in the interface itself. Other forms of tangible interfaces can be stateless such as free spinning dials. For the purpose of these experiments, a stateless tangible object is required. A hockey puck was selected to represent a stateless tangible dial. By using the hockey puck interface, the user interface could be reset programmatically after each question without needing the tangible object to change.

The Microsoft Surface's ability to recognize tags allowed a hockey puck to be an effective input device. To track the puck, a tag sticker was placed in a way that it was in contact with the screen. While exploring the Surface's tag tracking support, it was determined that the tags are tracked best when it was the only part of interface in contact with the display. Testing of the new interfaces also showed that if the tag was placed as close to the center of the object as possible, the tag acted as a pivot which the puck rotated around. Figure 3-2 shows the bottom of the puck that was used for all participants in both experiments.



Figure 3-2: The underside of the hockey puck showing the Surface Tag.

The tag tracking functionality provides developers with a set of messages about the object(s) being tracked. First, the “contact down” message was created whenever a tagged object was first tracked by the Microsoft Surface. The most common message was the “contact changed” message. Whenever the surface was able to notice that the position or orientation of the tag has changed, the “contact changed” message was passed to the application along with both the new position and orientation of the tag. The position information passed were the X and Y coordinates referencing the upper-left corner of the screen. Included in the “contact changed” message was the orientation of the tag in relation to the surface. The 0° reference occurred when the

tags value, “40” in the case of Figure 3-2, was upright as seen by the surface sensing system below the screen. The possible values of the orientation were the range from from 0° inclusive to 360° exclusive. When the tag was rotated to the right, the values increased and when rotated to the left the orientation value decreased, resetting to 360° when passing the 0° point. The final message passed for a tag was the “contact up” message which occurred when the surface was not able to locate the tag.

All of the messages described above were consumed by the software associated with the Physical Puck interface. When the “contact down” message was sent, the graphical portion of the user interface, seen in Figure 3-3, was displayed surrounding the device. Each time the “contact changed” message was received, the graphical interface would either change position based on the x and y location or the yellow line which, indicated the location within the data set, would change if there was a change in the orientation of the puck. Finally, when the “contact up” message was received, the graphical portion of the display would be removed from the screen.

3.2.3.1 Coarse Motion Control

To ensure that the physical portion of the physical puck interface was stateless, the coarse motion element for the interfaces was fulfilled with a touch interface. The upper half of the puck had a semi-circular scrubber positioned above it. Figure 3-3 shows the graphical element used for the Physical Puck interface. To ensure that the length of the scrubber element was not a factor for the data analysis, the center of the arch’s length was matched to the length of the scrubber in the control interface. Figure 3-4 shows how the scrubber element was incorporated into the final Physical Puck Interface. 3-4 also shows the final element of the Physical Puck interface, a yellow line as an indicator of the current selected time. The yellow indicator showed the selected position in the data set and provided the Physical Puck interface’s method for coarse motion.

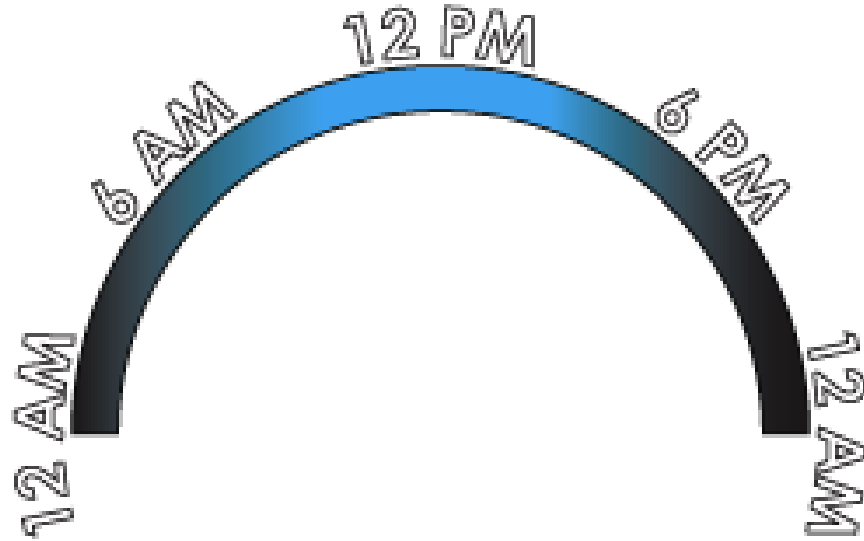


Figure 3-3: The coarse motion user interface for both Physical and Virtual Puck interfaces.

To use the coarse motion of the interface, the user placed their finger on or near the yellow line and then moved around the display. The act of placing a finger on the yellow line “grabbed” the indicator. Once the indicator had been “grabbed”, users were then able to change its position by moving their finger around the screen. Throughout the motion of the users finger, the indicator would move as if it was part of a line segment from the users finger to the center of the puck. If a user moved their finger below the scrubber element, the indicator would remain in the last valid location. For example, if the user scrubbed all the way to the left “12 AM” and then continues below the interface, the indicator will remain at “12 AM”. When the user wanted to stop scrubbing, removing their finger from the display would stop the indicator at the last valid indicated position. In some cases, “Lift Off Error” occurred, resulting in the indicator moving to an undesired position. Dependent upon the user’s preference and the movement caused by the error, users could initiate another coarse motion interaction or switch to the fine motion control for the correction.



Figure 3-4: The completed Physical Puck Interface.

In the development of the scrubber interface, only a 180° arch was selected to allow possible expansion. In future work, other controls could be added to the same interface which could reside in the lower half of the interface.

3.2.3.2 Fine Motion Control

The hockey puck provided fine motion control for Physical Puck interface. Our intention was to create an interface that was not only easy to use but intuitive. When users wanted to use fine motion control, they rotated the puck in whichever direction they were interested in traversing data. For example, to go later in time, a user rotated the puck to the right, and to go earlier in time, the puck could be rotated to the left. Using the physical object as an interface component allowed the subjects to use more than one finger to manipulate the interface. Having more than one method to interact with the device may have provided users a more natural feeling of interaction depending on their preferences.

When a user turned the puck, the interface’s software controller determined when the selected data point changed. During the development of the Physical Puck interface, an angle of 7.5° between data points was selected. 7.5° was determined through analysis of log data and an informal user study. Out of all testing 7.5° had the most natural feel when scrolling through a large amount of data. Informal user studies before the experiment found that subjects could get within 30 points of the desired data point using the coarse motion interface. Using 7.5° per data point results in 48 data points per rotation of the puck and, in many cases less than one rotation of the puck after coarse movement to reach the desired location. Also during the testing, there were some cases where a rotation of one to two degrees occurred when releasing the puck. With 7.5° per data point, liftoff rotation error was greatly reduced.

3.2.3.3 Movement

One shortcoming of the fine motion control portion of the Physical Puck interface was the amount of screen space that was consumed when it was being used. The Mapping Application took advantage of the screen size by using as much of the display as possible. During some questions, the interface occluded sections of the screen which had useful information. To permit the application to use all of the display while not occluding portions of the view the puck could be moved around the screen. When the puck was moved, the rest of the interface moved along with it. By allowing movement of the interface, any occlusion that occurred could be resolved by changing the location of the interface.

3.2.3.4 Design Requirements

In Shneiderman’s work, three requirements for user interfaces were presented which the Physical Puck interface includes [26]. First, the Physical Puck provided a constant representation of the interfaces state by using the yellow line in the scrubber

section of the interface. The yellow line continuously showed the region of the selection within the full 24 hour data set. Second, all interactions with the Physical Puck interface were click and drag, rotation or movement based. To use the Physical Puck interface, the user did not have to learn any complicated gestures or syntax. Finally, all actions taken by the user are easily reversible. If the user scrubbed too far past the desired point they could move the scrubber back, if they went past the desired point with the puck they can simply rotate the other direction.

3.2.4 Virtual Puck Interface

After creating the Physical Puck interface, we determined that only testing against the control interface was not sufficient. With the drastic change in the look and usage between the control and Physical Puck interface, a third interface was created that was similar in design to the Physical Puck and used only direct touch. To fulfill the requirements, the Virtual Puck interface was created. Figure 3-5 shows the completed Virtual Puck interface.

The primary difference between the Virtual Puck interface and the Physical Puck was the removal of the hockey puck which was replaced by a grey circle. When switching from the hockey puck to a grey circle, two changes were made. First, the visual representation for the fine motion control was amended to include visual markers. The blue circle at the edge of the grey circle was added to give the user a visual cue for the orientation of the interface. The addition of the blue circle took the place of any scratches or other markings on a physical object. In addition to the blue dot there was a black dot at the center of the grey circle. If a user was quickly spinning the interface or lost focus and crosses the center of the interface, the system would register that the interface had rotated 180°. In most cases skipping 180° was an unwanted result. The addition of the black dot was intended to provide another visual cue to prevent users triggering the unwanted jumps.

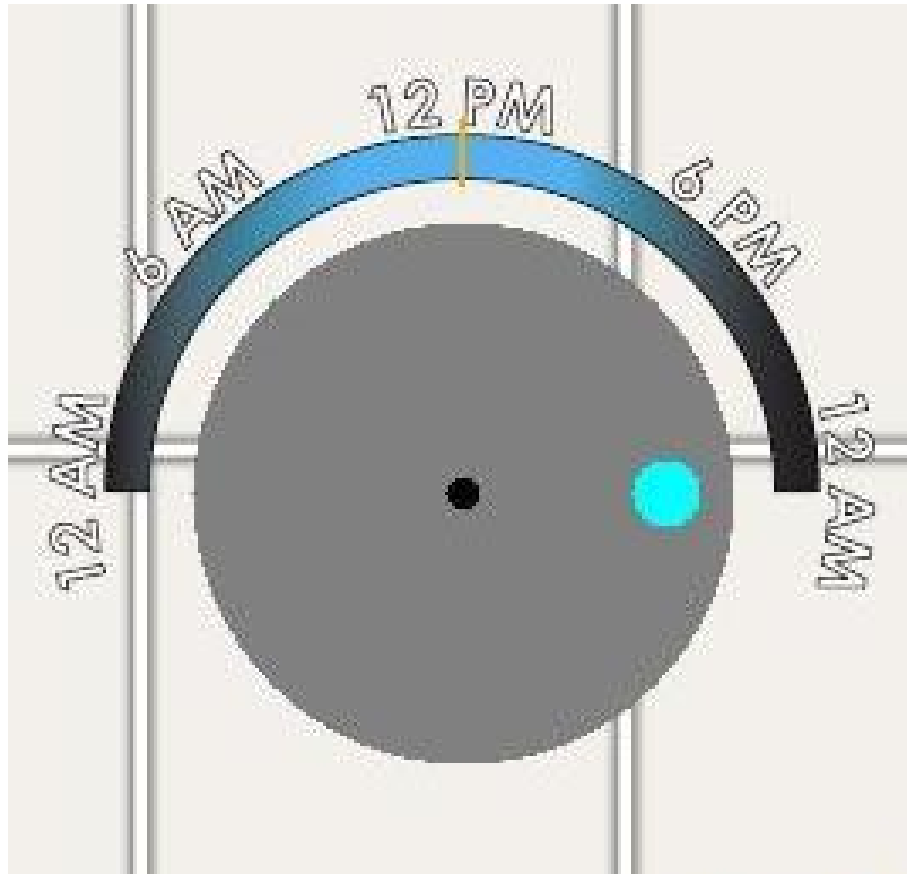


Figure 3-5: The completed Virtual Puck Interface.

The second major change made was the addition of a gesture to move the interface around the display. In contrast to the Physical Puck interface, using one finger on the Virtual Puck interface to move it would result in the selected value changing rather than moving the interface itself. A gesture of two fingers inside the grey circle was used to initiate any movement. Once the movement was started, both fingers had to remain in contact with the display until the interface was at the desired location. When the movement was completed, the user could then remove both fingers and the interface would be fixed in that location until another move event was started.

Other than the method to move a control, all the requirements set by Shneiderman are fulfilled in the same way for the Virtual Puck as they were for the Physical Puck.

The gesture to move the interface was more complicated but it was still fairly simple and did not require much thought after it had been learned. We argue that the new gesture was not considered complicated and that Shneiderman’s requirements were upheld.

3.3 Development of the Testing Applications

For the two experiments in the following work, two different applications were created to test different types of user interactions. First, an application for exploring time-coded and geocoded data was created which, provided questions for its users to answer about vehicles traversing a fictitious map. Going forward, the time-coded and geocoded data application will be referred to as the “Mapping Application”. The second application was designed to redirect the users gaze to a second screen in an attempt to use an eye tracking system to follow their gaze and to track the subjects pupil diameter. The second application was be referred to as the “Numbers Application”. The two following sections will describe both applications in detail.

3.3.1 Development of the Mapping Application

3.3.1.1 Application Overview

As mentioned before, the Mapping Application was designed specifically to test the new user interfaces and how they could be used to review time-coded and geocoded data. A map was displayed and the user was asked to answer a question based on the track that a “vehicle” or a set of “vehicles” traversed. For each question there was at least one and sometimes two vehicle tracks displayed on the map and only one correct answer. Each individual track was in continuous motion for one period of time during each task. For example, if a track was in motion from 10:20 am to 11:32 am the track would not change position at any other time during the task. Four different question types were selected to test tasks with different requirements. The question design and

creation will be explained in later sections. For each interface tested, a total of three questions of each type were presented to the users, one being a practice question and two that were used for the analysis later. All questions were presented in a predefined, pseudo-random order that was maintained across all subjects. Finally, the order of presentation of the interfaces was counterbalanced to mitigate the learning effect for the application. The following sections will go into more detail on each of the major aspects of Mapping Application’s implementation.

3.3.1.2 Mapping Application

The goal of the Mapping Application was to implement a mapping system for a touch based display. For the Mapping Application, a mocked up street system was used to simplify both the creation of vehicle tracks and to remove any possibility that a user might have previous knowledge of the given map. Unlike common mapping applications such as Google Maps®¹, Bing Maps®² or Open Street Maps³, we were not interested in being able to resize, rotate or in any way change the display of the map. By limiting the need to manipulate the map itself, the background image, shown in Figure 3-6, was a fixed graphic which filled the entire display and could not be changed by the end user during the experiment.

To present the tasks to and accept answers for each task, a separate popup window was created. As seen in Figure 3-7, the popup window had the question at the top and a “Start” button at the bottom. When pressed, the “Start” button would both initiate the timing for each task and dismiss the question panel. When the popup window was opened to answer the question provided, the possible answers were displayed below the question. Before the user selected an answer, the “Answer” button was disabled. Figure 3-8 shows how the question popup window appeared after the user’s answer had been selected. When the user had selected their answer, pressing the “Answer”

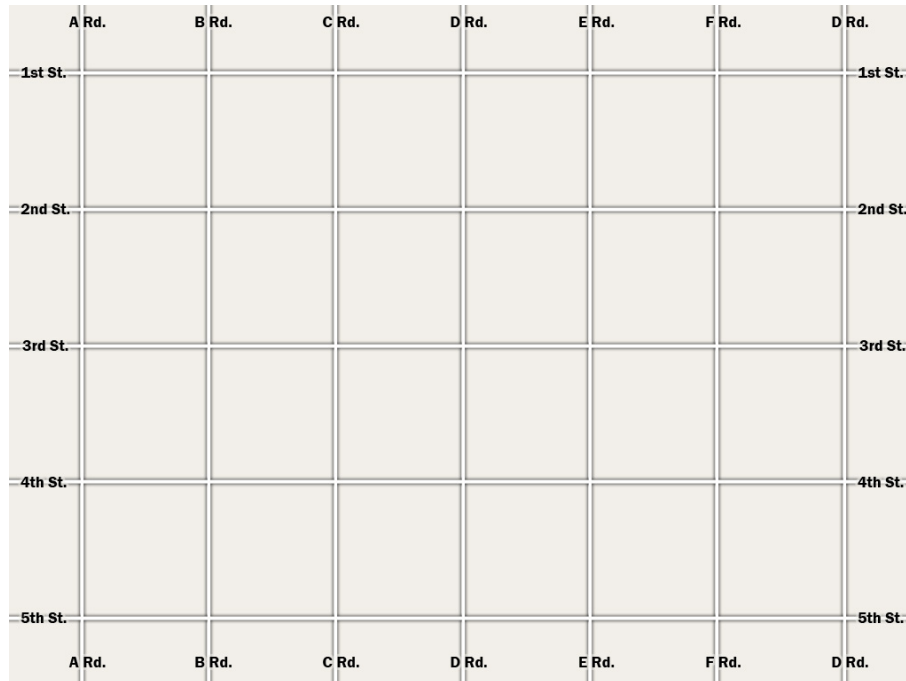


Figure 3-6: The mocked up grid based street pattern used for the Mapping Application.

button would stop the timing for the task and present the next question, if available, or complete the section.

To control the question window from the map screen, two buttons in the lower-center of the screen, shown in Figure 3-9, enabled the user to recall the question popup window for two reasons. First, if the user needed to review the question, the green “Review” button would display the original question window as seen in Figure 3-7. Second, the red “Stop” button displayed the question popup window with the possible answers as described above.

The final components of Mapping Application were the time indicators, located in the lower-left and lower-right corners of the display. The time indicators displayed the current time within the active data set which corresponded to the data being displayed. Figure 3-10 shows one of the two indicators as it was displayed in the ap-

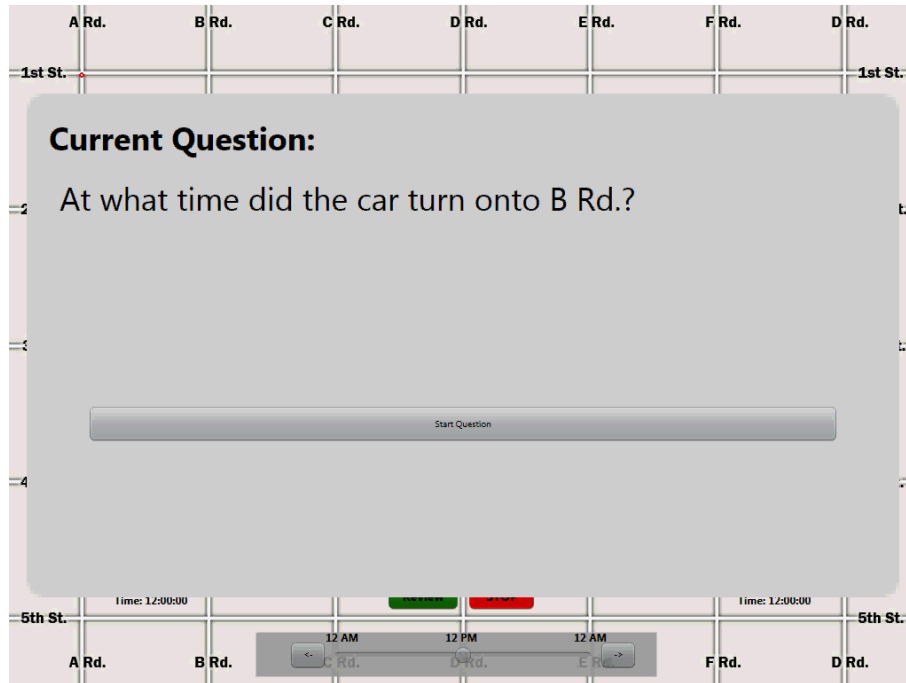


Figure 3-7: The popup window used to present each task to user.

plication. The time indicators served two purposes, first, the time indicators allowed users to accurately determine what time an event occurred in the active dataset. Also, having the current selected time displayed provided users a second, more accurate indication of their current position within the data set for their current task. As described by Shneiderman, these indicators were beneficial to most user interfaces used for the application by providing constant feedback of the interfaces current state [26].

To create a data rich environment, the sampling period of the data which was displayed was set to four times per minute (once every 15 seconds). A database was used to store the data points for easy extraction by both scripts for analysis and the experimental application itself. The creation and storage of the application information will be discussed in a later section.

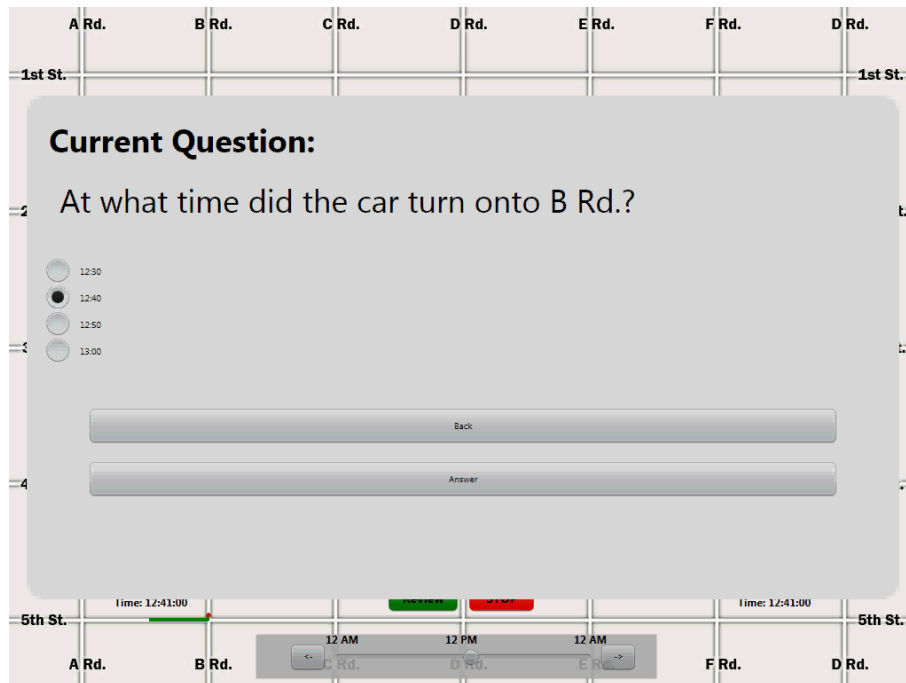


Figure 3-8: The popup window used to answer the question for each task. The answer had been selected and the “Answer” button was enabled.



Figure 3-9: The popup window control buttons in the lower-center of the main screen used to Review and Stop a question.

To easily integrate new user interfaces, an Application Programming Interface or API, described in the next section, was implemented. The API connected the Data Controller to any new interfaces. The Data Controller was a piece of software within each application that was responsible for maintaining the current state of the system as well as properly filtering the requested data from the data storeage. When one of



Figure 3-10: One of the two time indicators displaying the time selected by the user.

the tasks began, the Data Controller requested all of the data points for the specific task. Once all of the data had been gathered, a separate View Controller was passed two minutes of data prior to the current point selected. The View Controller then displayed the points it had been passed on the application's map. For the Mapping Application, the View Controller only received messages from the Data Controller.

3.3.1.3 User Interface Application Programming Interface

To ease the development of new user interfaces, the Mapping Application exposed an API that allowed a new user interface to easily control the application in a predictable way. The API also allowed the data controller in the application to pass messages back to the interface. Table 3.2 below is a list of all messages that are implemented by the Data Controller. The first row of each entry shows command name as well as sender and receiver of the message. The final value of the first row is the datatype of the message that was passed. The second row of each entry is the a short description the what the API call is used for. The description also explains how the value of the message, if one existed, was used by either the application or the user interface.

Command	Sender	Receiver	Message Data Type
	Description of Command Actions		
Initialize	Data Controller	User Interface	None
	Signaled the user interface to initialize itself in preparation for being displayed.		
Set Minimum	Data Controller	User Interface	Integer
	Used to set the minimum possible index for the data range.		
Set Maximum	Data Controller	User Interface	Integer
	Used to set the maximum possible index for the data range.		
Paint	Data Controller	User Interface	Display Graphic Object
	Signaled the user interface to display itself or to update its current graphical representation.		
Increment	User Interface	Data Controller	None
	Used to signal the data controller that the user has changed the selected value by one in the positive direction.		
Decrement	User Interface	Data Controller	None
	Signaled the data controller that the user had changed the selected value by one in the negative direction.		
Set Value	User Interface	Data Controller	Integer
	Signaled the data controller that a user had changed the interface's by more than one data point in either direction. A positive value would increase a negative value would decrease.		
Reset	Data Controller	User Interface	Integer
	Signaled the the interface to reset itself to the point that was passed.		
Close	Data Controller	User Interface	None
	Signaled the interface that it was no longer needed.		

Table 3.2: The messages allowed messages for the Application Programming Interface between the User Interface and the Data Controller within the Mapping Application.

3.3.1.4 Track Creation and Storage

To create the vehicle tracks for the Mapping Application experiment, a web application was created. The application allowed the experiment designer to point and click on the intersections of interest in the order that they wished for the intersections to be traversed in the data set. Figure 3-11 shows a screenshot of the web interface to create the tracks.

(0,0)	(0,1)	(0,2)	(0,3)	(0,4)	(0,5)	(0,6)
(1,0)	(1,1)	(1,2)	(1,3)	(1,4)	(1,5)	(1,6)
(2,0)	(2,1)	(2,2)	(2,3)	(2,4)	(2,5)	(2,6)
(3,0)	(3,1)	(3,2)	(3,3)	(3,4)	(3,5)	(3,6)
(4,0)	(4,1)	(4,2)	(4,3)	(4,4)	(4,5)	(4,6)

Track Name:

Starting Time:

Wait Time: seconds

Figure 3-11: A screen shot of the vehicle track creation web application’s interface.

The creation of a track with the web tool was very simplified. First, the experimenter selected name and a start time for each track. The time selected was when the data first appeared on the screen. Once the start time and name had been entered and the “Set” button pressed, a start point on the grid was selected. Each of the points of the grid, shown in Figure 3-11, corresponded to an intersections in Figure 3-6 above. For example, “(0,0)” on the web interface represented the upper-left intersection on the grid system. Once a starting point had been selected, the interface automatically disabled intersections that were not in the same column or row as the selected intersection. Disabling the intersections as described, all vehicles traveled

on one of the streets or roads at all times. When the designer finished creating the track, the “Create Track” button was pressed to finalize all of the selected points. When finalizing the track, the web interface generated a data set corresponding to the intersections selected. The new data set was made by calculating the vehicle’s location every 15 seconds as specified earlier. The sampling frequency was selected to two reasons. First, having 5760 data points (4 samples per minute for 24 hours) limited the memory footprint for the application. By using a smaller amount of memory, the processing time needed to change the display for each interaction was reduced, making the application respond faster to change. Second, when a sampling period of 4 times per minute was selected, scrolling through data appeared fluid while still maintaining the small memory footprint.

One element of the web interface displayed in Figure 3-11 was the “Wait Time” field. The wait time was implemented to allow cars to stop at intersections for a specified number of seconds. During the development of the experiment, we determined that having cars start and stop during duration of its movement could confuse the user so “Wait Times” were not used for any tracks in the Mapping Application experiment.

For the Mapping Application experiment, the start times were partitioned into four ranges outlined in Table 3.3. When a task started, each interface was initialized to 12 PM, the center of the 24 hour time frame. The four ranges were grouped into two sections around the center point of the time windows. The first ranges were close to the center (10 AM and 2 PM) and the second ranges further from the center (6 AM and 6 PM). The two groups were created to ensure that the users would use the coarse motion interface rather than just the fine motion for maneuvering to the data. Having multiple ranges for when the task data started also reduced how effectively users could predict where in the data set the vehicle would be moving. Each of the

ranges also had a range allowance associated with them. The allowance corresponded to a variation for the start time of a task. For example, if a question was in the 6 AM range, the actual start time could have been anywhere from 5 AM to 7 AM. The range allowance for the 10 AM and 2 PM ranges were made smaller to ensure that no data would overlap the mid point of 12 PM for any reason.

Table 3.3: Data set start times and range allowances for the Mapping Application

Time	Distance from Center	Range Allowance
6 AM	6 Hours	+/- 1 Hour
10 AM	2 Hours	+/- 30 Min
2 PM	2 Hours	+/- 30 Min
6 PM	6 Hours	+/- 1 Hour

3.3.1.5 Question Design

Each of the unique tasks participants were asked to complete were based on a question. Each question referenced either a single dataset or two related datasets as described in Section 3.3.1.4. In order to evaluate different mental tasks for each interface, four question types were used. The set of questions was designed to require specific interactions as well as trigger specific manipulations with the interfaces. The question templates that were selected can be found in Table 3.4.

Table 3.4: Experiment question templates for the Mapping Application

Question #	Question Format
1	Did the car turn onto X road / street?
2	When did the car turn onto x road / street?
3	On what road / street did the cars pass?
4	How many times did the cars pass each other?

For each question there were four factors identified which could separate one question from another. For the Mapping Application, a stationary Point of Interest (POI) was defined as a point on the grid system, such as a street or intersection. Also a moving POI was a specific point of time for one or more vehicles interacted with the map or each other, an example of a moving POI was two vehicles passing each other. In addition to POIs, it was important to evaluate how many times the question's condition was met. For most questions, the number of matches was one but for question type four, participants were required to count the number of matches that occurred.

In some cases, users could quickly review the data to see if an event occurred, looking for if something happened or not careful review of all provided data was not necessarily required. In other cases users were expected to use fine motion control. Table 3.5 shows a comparison of stationary and moving POIs as well as the number of matches that the subject had to look for. Table 3.5 also includes a column indicating which questions were intended to include at least some use of fine motion control.

Table 3.5: Question point of interest(POI) types and motion types by question type for the Mapping Application

Question #	# of Stationary POI	# of Moving POI	# of Matches	Requires Fine Motion Control
1	1	1	1	No
2	1	1	1	Yes
3	1	2	1	Yes
4	0	2	≥ 1	Yes

Each of the question used were broken down into basic steps as shown in Table 3.6. Each step of a question had two factors listed in the table. First is the movement type. Smith et al. separated data navigation into three different movement types as seen in Table 3.1 [27]. Smith et al. also stated that a user interface should allow its users to rapidly search through data while both utilizing minimal screen space and

the ability to select a single item. These principles were applied to the design of the interfaces in Section 3.2. For both experiments, the interfaces were reduced to two control methods by incorporating gross and portions moderate movement into the same section of the interface, relying on the user to alter their movements accordingly. The second factor states if all of the data for a vehicle’s track had to be reviewed in order to find the correct answer. Unlike the first three question types, reviewing all of the data for the fourth question is crucial to ensure that the correct answer was found.

Table 3.6: Question steps by question type for the Mapping Application.

Question Type	Step	Movement Type(s)	Review All Data
1	a) Find the dataset	Gross / Moderate	No
	b) Find when car location = provided location	Gross / Moderate	No
	c) Answer multiple choice	N/A	N/A
2	a) Find the dataset	Gross / Moderate	No
	b) Match the car to the given location	Fine	No
	c) Answer multiple choice	N/A	N/A
3	a) Find the dataset	Gross / Moderate	No
	b) Match the location of the two cars	Fine	No
	c) Answer multiple choice	N/A	N/A
4	a) Find the dataset	Gross / Moderate	No
	b) Count the number of passes	Fine	Yes
	c) Answer multiple choice	N/A	N/A

To simplify the processing and the analysis of the experiment data, we tried to create tasks with similar steps. The first step of each question type was to find the dataset from within the full timeframe. The process of finding the data did not require the participant to pinpoint a POI accurately so it was be classified as gross or

moderate movement. Also, the final step of each question was to answer a multiple choice question. The multiple choice step did not involve interaction with the data set, so no movement type was associated with it. The only difference with the procedure for each question was the middle step. The next four sections will discuss the design for each question and how it attempted to provoke the movement types seen in Table 3.6.

3.3.1.5.1 Question Type 1 *Did the car turn onto X road / street?*

Question type 1 was designed to test the participants ability to quickly scroll through data and determine if an event occurred or not. Assuming that the participant was able to manipulate the data at a moderate speed the answer of the question would have been apparent without requiring much, if any, fine control. Additionally, if the participant did not move too quickly through the data, there would not have been a need to scroll back through any of the data. Question type 1 required the user to match one moving POI, the vehicle, to one stationary POI, the street or road. During the Mapping Application experiment, the vehicle would only travel on the given road or street once. The possible answers for questions type 1 were "Yes" and "No".

3.3.1.5.2 Question Type 2 *When did the car turn onto x road / street?*

Question type 2 was designed to test the participants ability to use the gross/moderate movement to get near a POI and then use the fine control to locate the exact POI. For question type 2 the POI was a point in time where the vehicle changed coarse onto a selected street or road. Similar to question type 1, the participants had to locate the point where the vehicle was on the requested road or street. Once a point was found on or near the street/road of interest, the user had to use fine control to find the exact POI. Question type 2 required that the vehicle only turned onto the

street or road once to limit the number of answers to one. Question type 2 limited the number of stationary POI's to 1, moving POI's to 1 and the number of matches required to 1. The possible answers for the question type were a set of timestamps with only one correct answer and all others being at least 4 data points (1 minute) away from the correct answer.

3.3.1.5.3 Question Type 3 *On what road / street did the cars pass?*

Unlike the previous two question types, question type 3 integrated a second vehicle. Another change introduced with question type 3 was the number of POIs involved. Question types 1 and 2 required that the user watch for a vehicle to travel on a particular road or street. In the case of question type 4, the user had to look for the time when two vehicles passed and then determine on which road or street the pass occurred. As with the previous question types, there was only one correct answer within the data set. Four possible answers were provided with only one being correct.

3.3.1.5.4 Question Type 4 *How many times did the cars pass each other?*

The final type of question was similar to the third, but involved no stationary POIs. Two vehicles moved throughout the grid system and passed each other number of times greater than or equal to one. Unlike the other question types, there was not stationary POI. Question type 4 was designed to be an analog for other forms of data, not just geocoded data sets. There were four choices for question type 4 with one correct answer.

3.3.1.6 Question Creation Interface

A second web application was created to aid in the creation of questions. As seen in Figure 3-12, the question generate application had a set of options that the experimenter filled out when creating a new question. First, a question type had to

be selected. Each of the question types corresponded to one of the question types from Section 3.3.1.5 above. For questions types 1 and 2, the “Track 2” and “Track 2 Offset” fields were not necessary and were hidden from the designer. Additionally, for the question types 2 through 4, four option fields were presented below the “Track 2 Offset” field with the labels “Option 1” through “Option 4”. The four fields corresponded to each of the four multiple choice answers which were displayed to the user during the experiment. Also, a radio button was positioned to the right of each of these fields which, when selected, was used indicated the correct answer for the question. The “Question Text” field was where the designer entered the question that was displayed to the users in the question popup windows. Finally, the track(s) for the question were selected by using the drop-down field(s) next to the “Track 1” and if applicable “Track 2” headings. The values in the drop down were populated from the data created by track creation tool covered in Section 3.3.1.4. If for any reason the start time of a track was incorrect, the “Track Offset” field of either track could be used to shift each track’s data points by the number of minutes in either direction.

3.3.1.7 Application Logging

All log messages were stored both locally and in remote database during the Mapping Application experiment. For each log entry, there was a separate line. Each log line consisted of a timestamp with milliseconds precession, a line identifier and a log message. All possible types of log line identifiers and the data that was contained in the message can be found in Table 3.7. As seen in the Table 3.7, the events recorded relate to both finger and tagged object interactions as well as the state of the system.

All log data was written to a database to allow the experiment proctor to see in real time how many tasks had been completed. Logging to a database also added the ability to write specific database queries to analyze data by taking advantage of the database engine rather than custom scripting.

New Question:

Question Type:

Question Text:

Track 1:

Track 1 Offset: Min

Track 2:

Track 2 Offset: Min

Figure 3-12: A screen shot of the question generation web interface for the Mapping Application.

3.3.1.8 Interface Presentation Ordering

To account for the learning effect, the Mapping Application was designed to predictably select an order for interfaces based off of the user ID. The remainder of user ID divided by the factorial of the number of interfaces was used to determine the order ID (3.1). From there the Order ID was used to determine the order in which the interface appeared. The Order ID and interface presentation pattern can be found in Figure 3.8.

$$\text{OrderID} = (\text{UserID})_{\text{mod}}(\text{NumberOfInterfaces})! \quad (3.1)$$

3.3.1.9 User Training

Once the subject was in a comfortable position to use the Microsoft Surface, a video was shown to instruct them on what they were asked to do during the experi-

Table 3.7: Possible log lines for the Mapping Application.

Logged Event	Data Contained
Start of Experiment	No Data
Finger Contact Down	The x and y location of the finger
Finger Contact Changed	The new x and y location of the finger
Finger Contact Up	No Data
Tagged Object Contact Down	The x and y location as well as the orientation
Tagged Object Contact Changed	The new x location, y location and orientation
Tagged Object Contact Up	No Data
Task Number	The new task number
Selected Value	The index selected in the data set when changed
Button Presses	The name of the button pressed
Answer Correctness	An indication if the answer selected was correct
End of Experiment	No Data

Table 3.8: The order of interface presentation by order ID

Order ID	First Interface	Second Interface	Third Interface
0	Control	Virtual	Physical
1	Control	Physical	Virtual
2	Virtual	Control	Physical
3	Virtual	Physical	Control
4	Physical	Virtual	Control
5	Physical	Control	Virtual

ment. The video walked the subjects through how the three section of the experiment, one for each interface. The overview video explained that each section started with a training video that reviewed the features of the interface, followed by the practice questions and then the measured experiment questions.

The bulk of the video demonstrated how one of the questions worked from start to finish. First, the question dialog was shown, the dialog was used to provide the question for each task. The video then went on to explain how the vehicle(s) moved around the grid system. Finally the video explained that when the user had found

the answer for the given question, they had to press the “Stop” button, select the answer and then press the “Answer” button to move onto the next question.

The training also included a trial run of the NASA-TLX assessment. Users were asked to consider any task from their day, and answer the questions for the NASA-TLX assessment when considering the selected task. To aid the subjects, Appendix C was provided as a printout. The printout had a list of the metrics and their definitions for the assessment. During the trial and all subsequent assessments during the experiment, no time limit was set allowing user to complete the assessment to the best of their ability.

3.3.1.10 Interface Training

As stated in the User Training section, before each section of the experiment, a short video demonstrating the use of the user interface was shown. The format for all three videos was the same to reduce any bias that may have been introduced by the presentation. Each video started with an overview of the interface. The interface overview showed users how to move quickly through the data in either direction using the scrubber and also how to increment and decrement with the fine motion control. When applicable to the interface, the method for moving the interface around the display was demonstrated.

The overview section was followed by a recorded demonstration of the interface being used in an example task. The demonstration started with a question panel showing an example question. The demonstration user pressed the “Start” button and then used the specific interface to locate the answer to the question. While the demonstration user was looking for the answer, they went through all four methods of moving through time (scrub forward, scrub backward, fine forward and fine backward). If the interface was able to move around the screen, the video show the gesture

after the answer had been found. Finally, the user selected the “Stop” button, then the answer and finally the “Answer” button to complete the task.

3.3.1.11 Question Presentation Ordering

To account for possible bias introduced by any questions, the order of presentation was fixed independently of the interface used. For each of the four question types defined in Section 3.3.1.5, there were two created for each section of the experiment. Each section of the experiment had eight questions which were used for testing and four practice questions. The questions for each section of the experiment were arranged in such a way that no two question of the same type were presented one after the other.

3.3.2 Development of the Numbers Application

The Numbers Application was very similar to the Mapping Application in design, with some minor changes in how information was displayed. Unless noted below, each of the sections in Development of the Mapping Application, Section 3.3.1, apply here as well.

3.3.2.1 Application Overview

The Numbers Application was designed to test only the user interactions by using a simplified task rather than the more difficult and varying tasks of the Mapping Application. The design for the Numbers Application was based off of the work of Ahlberg et al. when testing the Alpha slider [2]. The task for Ahlberg et al.’s study was to find one entry in a list of 10,000 sorted movie titles. Rather than using a sporadically distributed list of movie titles, we chose to use an integer list from 1 to 10,000, creating a very predictable dataset.

3.3.2.2 Numbers Application

The Numbers Application was designed to allow users to find a given value within a dataset. Two displays were used for the Numbers Application as seen in Figure 3-13. The lower, horizontal screen, was used for the user interfaces as well as starting and stopping the timing for each task. The lower screen accepted both touch and object input while also displaying any user interface components that were not physical objects. To start and stop the timing for each task, a single button located in the bottom-center of the screen was used. The start and stop button was present throughout the entire experiment. The upper screen was only used for output as seen in Figure 3-14. On the upper screen there were two numbers displayed, the top black number represented the number that the users were asked to find and, the lower red number which was the value that was selected. During the experiment, the users were asked to match the red value to the black as quickly as possible.



Figure 3-13: The setup of the horizontal and vertical screens for the Numbers Application experiment.



Figure 3-14: A screen shot of the Numbers Application's vertical display showing the target number in black and the selected value in red.

3.3.2.3 Task Design

Like the Mapping Application, each task started at the center point of the total data set, for the Numbers Application 5,000 was the center. Also similar to the Mapping Application, multiple ranges around the center were defined where the target values were located. The ranges were centered at 250, 1000 and 2000 points away from the center with a variation of 50 points each as seen in Table 3.9.

3.3.2.4 User Training

Before the first section of the Numbers Application experiment, users were instructed on the format of the experiment. Users were told that two numbers would appear on the upper display and that their task was to match the lower number to the top number as quickly as possible. When the instructions were covered, the upper

Table 3.9: The distance from the center of the data set, the range, and the variation for each range used when creating task for the Numbers Application.

Range Distance from 5000	Range Center	Range Allowance
2000	3000	+/- 50
1000	4000	+/- 50
250	4750	+/- 50
250	5250	+/- 50
1000	6000	+/- 50
2000	7000	+/- 50

display showed the upper black and lower red numbers as 5000. Finally, users were instructed that the button on the lower screen, which was visible to them at the time, was used to start and stop the tasks.

3.3.2.5 Interface Training

Before each section of the Numbers Application experiment, users were instructed on how to use the interface for that section by the experimenter. Users were shown how use each interface's fine and coarse motion methods were used as well as how to move the interface if applicable. The instructions presented were very similar to the videos shown in the Mapping Application with the mapping specific segments omitted.

Once the user instruction was completed, each user was presented with three practice questions. The practice question allowed the subjects the opportunity to explore the interface and, ask any questions they had about it's proper use. The practice questions involved one from each Range Distance from the center point, listed in Table 3.9 with at least one from each side of the center point.

3.3.2.6 Task Presentation Ordering

The numbers that users were asked to find were selected before the experiment and appeared in the same order for all subjects independent of user interface. Each of the ranges had two tasks per interface for a total of 12 tasks per interface and 36 tasks for overall. No two tasks from the same range were presented one after the other.

3.4 Experiment with Human Subjects

3.4.1 Mapping Application

3.4.1.1 Subjects

To gather participants, an email was sent to the College of Engineering and Physical Sciences at the University of New Hampshire requesting participants to partake in a tangible user interface interaction study. Care was taken in gathering multiples of six participants for each gender to allow counterbalancing within each gender.

3.4.1.2 Procedure

When the subject arrived for their scheduled experiment slot, they were asked to fill out the consent and release form found in Appendix A. Following the consent and release form, subjects were asked to complete the Personal Information Questionnaire found in Appendix B to gather demographic information and information about prior usage of touch screens, Mapping Applications and tangible user interfaces.

Once the paperwork was completed, preparation for the experiment began. First, subjects were instructed on the proper placement of the EKG electrodes and were asked to use the restroom to position them. Once the subjects returned, a skin conductance probes were placed on middle and index finger of the subjects non-dominant hand. The leads from both physiological measurements devices were attached to a data logging device which was used during the experiment. To ensure that the place-

ment of all the probes was correct, the readings were tested by attaching the data recording device to a workstation that could process the data in real time. In the event that the data was invalid the subjects were asked to reposition the probes and then the readings were retested until the data was viable for later analysis. Once the probes were able to gather valid data, subjects were asked to sit at a traditional computer workstation. At the workstation, they were asked to complete the NASA-TLX assessment. Every time subjects were asked to complete the NASA-TLX assessment, the list of definitions from Appendix C was provided on paper for the subjects to consult. After the NASA-TLX assessment was completed, subject moved to sit in front of the Microsoft Surface which was already running the Mapping Application.

When the subject was in a comfortable position, the overview video as described in Section 3.3.1.9 was shown to explain the experiment which was followed by a chance to ask any questions they had. After the overview video, another video, as described in Section 3.3.2.5, was shown explaining how to interact with the first interface. The first interface video was also followed by a chance for the subject to ask any questions before the questions started to appear.

After any questions had been answered, the practice section of the experiment started with four tasks. Once all four practice tasks were completed, the subjects had a chance to ask any new questions before moving on to the measured questions. Upon completion of the eight testing question, they were prompted to switch back to the other workstation to complete the NASA-TLX assessment while considering only the eight tasks they had just completed. When the assessment was over the subject moved back to the Microsoft Surface and repeated the process of video, practice, tasks and NASA-TLX two more times for the remaining two interfaces. When all three sections of the experiment had been completed, users were given a second questionnaire which covered questions about the all of the measured tasks of the

experiment. The second questionnaire can be found in Appendix E. After the user had completed the questionnaire, they were asked to remove the probes, were given their compensation and thanked for their participation.

3.4.1.3 Data Collection

Throughout the experiment, data was collected in multiple formats. As covered in the procedure, Section 3.4.1.2, two questionnaires were filled out by each of the subjects. Both surveys were administered on paper and entered into a spreadsheet after the experiment had been completed. Another subjective measure gathered was the NASA-TLX assessment data. All NASA-TLX assessments were administered on a computer and stored in an Excel file format. Following the experiment, the NASA-TLX data was saved for later analysis. For all interactions during the experiment, the application logged data directly into a database as described in Section 3.3.1.7. Logging directly to the database ensured that the data was available to programmatic analysis later without a need for complicated parsing of log files. The physiological data gathered during the experiment was recorded onto a measurement logging device. At the start of each section of the experiment, the Mapping Application synchronized timing between itself and the measurement logging device for the physiological measurements which could be extracted during the analysis process. When the experiment was completed, all data from the data logger was exported and manually process to remove any apparent noise in the signal. Once the signal was reviewed, the results were stored in a MATLAB format for processing later.

Video was the last form of data collected. Throughout the Numbers Application experiment, three cameras were positioned around the room capturing different angles of the subject and the Microsoft Surface. The first angle was a top down view. The top down angle captured the Microsoft Surface, the subject and a minimum of one foot around the subject to capture any movement near the interface. The second

angle was a camera at the subject's eye level facing them. The eye level cameras view also included the surface but was also useful for determined if any part of the subject's hand was in contact with the surface. The primary purpose of the first two angles was to have a record of how the subject interacted with the display. If there was an anomaly noticed when processing the data, the video would provide a method for determining what occurred. Finally, the third camera was fixed to the Microsoft Surface on the furthest edge from the user. The primary purpose of the surface mounted camera was to capture when the subject blinked. If the blink rate was captured successfully the relative cognitive load of the subject could be measured for each of the interface types.

3.4.2 Numbers Application

3.4.2.1 Subjects

Unlike the Mapping Application, the Numbers Application user study was not able to be run as a full experiment due to time constraints. In place of a full experiment, an informal pilot was conducted with the members of the Project54 lab as the subjects. The subject's familiarity with the Microsoft Surface and the Interfaces being tested varied between participants.

3.4.2.2 Procedure

The procedure for the Numbers Application study was less formal than the previous experiment. When the subjects arrived, they were instructed to sit at the Microsoft Surface in a comfortable position that allowed them to reach all of the horizontal display. Before any interaction began, the eye tracking system was calibrated to properly track the subjects eye gaze and pupil diameter.

Following the eye tracker calibration, subjects were verbally instructed on format of the experiment. Subjects were encouraged to ask questions about the format of the

experiment before the interface instructions began. Next, the first user interface was presented and demonstrated to the subject. When the subject was comfortable with both the experiment and the first interface, the first three practice tasks were started. After the practice set of tasks the 12 measured tasks were started as described in Section 3.3.2.3. The interface demonstration, practice and then 12 tasks was repeated two more times. Once all three sections of tasks were completed, subjects were asked to rank the interfaces in order of preference and then based on ease of use. Finally, subjects were thanked for their time and participation.

3.4.2.3 Data Collection

Like the Mapping Application experiment, the Numbers Application logged all interaction data to a database. The top down and user facing cameras were also reused for the Numbers Application experiment but the surface mounted camera was removed. No paper surveys were given but two verbal rankings were requested of each subject and recorded in a spreadsheet by the experimenter for later analysis. Finally, as a replacement for the third camera, an eye tracking system was used. The eye tracker was positioned between the horizontal display and the upright monitor as seen in Figure 3-13 and Figure 3-15. The use of the eye tracker in Numbers Application study was, like the third camera in the mapping application, was intended to estimate the cognitive load of the interface user. The positioning of the eye tracking system made it possible to track the subjects pupil diameter when their gaze was on the vertical monitor. As part of the design process, the Numbers Application moved as much of the subjects focus to the vertical display, allowing their pupils to be tracked for as much time as possible.



Figure 3-15: The vertical display setup for the Numbers Application also showing the location of the eye tracker.

3.5 Analysis of the Resulting Data

In the pursuit and investigation of our goals and hypotheses, we proposed two between-subject studies among males and females. Both qualitative and quantitative methods were used to analyze subject's data. For the Mapping Application, qualitative analysis was performed using data gathered from pre- and post-experiment questionnaires concerning subject's familiarity with touch based interfaces, mapping technologies, tangible user interfaces and usage preferences for the applications in both studies. For the Numbers Application, qualitative analysis was performed on the two subjective rankings from the subjects. The quantitative analysis for both experiments, outlined in the following section, categorized the usage of the different interfaces based on data gathered from the application logging, cameras and eye tracking devices.

3.5.1 Analysis of Quantitative Data - Mapping Application

As part of the procedure for the experiment, all data from the application logging and the physiological recording device were converted into a format which was able to be imported into MATLAB for further processing. A script was developed to extract a number of different values from all of the data imported. Tables 3.10, 3.11 and 3.12 have a list of all variables extracted, the type of data and a short description of what the value was a measurement of. One set of variables was created for every task presented to the user. Each of the values listed were analyzed and their results will be covered in the following chapter.

Unlike the values computed from the logged data, the information gathered by the video cameras could not be processed using the same MATLAB script. The primary purpose of the video was to provide a method to determine when the subject blinked. To extract the data from the video, each video was reviewed to note the time of each blink in relation to each task. We intended to enter the total number of blinks per task into each row of the data discussed before. The results of video data will be covered in the next chapter.

3.5.2 Analysis of Qualitative Data - Mapping Application

After each subject's quantitative data was extracted, the qualitative data from both questionnaires was entered into a common spreadsheet. In addition to the questionnaire data, the results from the NASA-TLX assessments were appended to the same spreadsheet. Each of the questions were analyzed independently to identify any trends. Finally, the NASA-TLX assessment results were analyzed to determine if any significant difference existed between the cognitive load estimates for each different interface.

3.5.3 Analysis of Quantitative Data - Numbers Application

The variables gathered from the Numbers Application were very similar to the Mapping Application. All physiological recordings present in the Mapping Application were omitted in the Numbers Application. With no data being recorded for physiological measurements, all heart rate, skin conductance values could not be calculated and were removed. Also, the camera positioned to capture the user blinking was removed for the Numbers Application experiment, removing the blink rate column from the data.

In place of the excluded measurements, the eye tracking system added a pupil diameter variable which was transformed into two sets of variables. First, the pupil diameter mean was added. The pupil diameter variable was very similar to the heart rate and was calculated by computing the mean over all valid pupil diameters for each task and the experiment overall. The second variable added was the pupil diameter standard deviation. The pupil diameter standard deviation was found by computing the standard deviation of all valid pupil diameters throughout the experiment and for each task. It was possible to extract the blink rate, but when users looked at the horizontal display, the eye tracker logged a blink rather than loss of tracking data.

3.5.4 Analysis of Qualitative Data - Numbers Application

After the Numbers Application experiment was completed, subjects were asked to order the user interfaces based on ease of use as well as personal preference. The ratings were collected in a spreadsheet for further analysis. Unlike the Mapping Application, the NASA-TLX assessment was not given between tasks for the Numbers Application.

3.5.5 Method for Analysis of Quantitative Data

Each of the quantitative values analyzed were processed in the same way. First, all data for one specific variable was entered into a spreadsheet to be processed. The spreadsheet used to process the data created a data table in a format that could then be used by SPSS. From the data entered, the mean and standard deviation were computed from all of the values provided. Any values that were greater than two standard deviations from the mean were excluded the remaining processing. If there was more than one data point per interface for each subject, the mean of all values for that subject was computed. Two separate data tables are created. The first table ordered the computed values by which interface was used while the second was the order in which they were presented to the user. The Repeated Measures analysis of SPSS was then used to process each set of data. Finally the data was reviewed and if possible any conclusions were drawn. The results of analysis will be presented in the next section.

3.5.6 Method for Analysis of Qualitative Data

For each qualitative variable, a table was created to visually identify if any trends was present. In the event that a trend was present, further analysis was done based on the trends noticed. The data analysis of the qualitative data will be shown in the next chapter.

Variable Name	Variable Data Type	Description
Subject ID	An integer greater than 0	The unique ID that was assigned to each user.
Overall Task ID	An Integer between 1 and 36 inclusive	The ID of the task within the experiment, 1 being the first and 36 being the last.
Section Task ID	An Integer between 1 and 12 inclusive	The ID of the task within the section, 1 being the first and 12 being the last.
Input Method	Either ‘Control’, ‘Virtual’ or ‘Physical’	The type of interface that was used for the task.
Start Time	Milliseconds from the start of the application	The time that the question popup window was first shown.
Start Button Time	Milliseconds from the start of the application	The time that the “Start Button” was pressed on the question popup window.
Stop Button Time	Milliseconds from the start of the application	The time that the “Stop Button” was pressed to display the question popup window
Stop Time	Milliseconds from the start of the application	The time that the “Answer” button was pressed in the question popup window.
Number of Reviews	An integer greater than or equal to zero	The number of times that the question was reviewed.
Coarse Motion Time	Time in milliseconds	The length of time that a subject used coarse motion control.
Coarse Motion Traversed	An integer greater than or equal to 0	The sum of the absolute value of all changes made with the coarse motion control where each 15 second data point is equal to 1.
Fine Motion Time	Time in milliseconds	The length of time that the subject used to fine motion control.

Table 3.10: A list of variable names, variable data types and variable descriptions for the data extracted from the Mapping Application (Part 1 of 3)

Variable Name	Variable Data Type	Description
Fine Motion Traversed	An integer greater than or equal to 0	The sum of the absolute value of all changes made with the fine motion control where each 15 second data point is equal to 1.
First Movement Time	Milliseconds from the start of the application	The time at which the first change in the selected time was made.
Last Movement Time	Milliseconds from the start of the application	The last time the selected time was changed.
Motion Transition Time	Milliseconds	The average time it took the user to transition from coarse to fine motion control or from fine to coarse motion control for the task.
Coarse Motion Points Per Second	Points per Second	The average number of data points traversed per second for the coarse motion control method.
Fine Motion Points Per Second	Points per Second	The average number of data points traversed per second for the fine motion control.
Total Points Traversed	An integer greater than or equal to 0	The sum of the absolute value of all changes made where each 15 second data point is equal to 1.
Total Motion Time	Milliseconds	The length of time between the first and last movement times
Total Time	Milliseconds	The total time from the question being shown to the “Answer” button being pressed.
Total Heart Rate Mean	Beats Per Minute	The mean of all heart rate measurements for the experiment
Total Heart Rate Standard Deviation	Beats Per Minute	The standard deviation of all heart rate measurements for the experiment

Table 3.11: A list of variable names, variable data types and variable descriptions for the data extracted from the Mapping Application (Part 2 of 3)

Variable Name	Variable Data Type	Description
Total Skin Conductance Mean	Microsiemens	The mean of all skin conductance measurements for the experiment
Total Skin Conductance Standard Deviation	Microsiemens	The standard deviation of all skin conductance measurements for the experiment
Motion Heart Rate Mean	Beats Per Minute	The mean of all heart rate measurements for the specific task.
Motion Heart Rate Standard Deviation	Beats Per Minute	The standard deviation of all heart rate measurements for the specific task.
Motion Skin Conductance Mean	Microsiemens	The mean of all skin conductance measurements for the specific task.
Motion Skin Conductance Standard Deviation	Microsiemens	The standard deviation of all skin conductance measurements for the specific task.
Review Time	Milliseconds	The total time the subject used the review question popup window, a value of 0 was possible.
Correct Answer	True or False	True if the subject selected the correct answer to the question.

Table 3.12: A list of variable names, variable data types and variable descriptions for the data extracted from the Mapping Application (Part 3 of 3)

CHAPTER 4

EVALUATION AND DISCUSSION

4.1 Mapping Application

4.1.1 Summary

As stated in Sections 3.5.1 and 3.5.2, numerous measurements were collected throughout the Mapping Application experiment. The following sections will review the results obtained from the analysis of the previously defined variables and some derived from one or more of the gathered values. The demographics and other subjective data gathered before the experiment will be examined first, followed by the data gathered from the experiment and finally the data from the post experiment questionnaire will be reviewed. Chapter 5 has a discusses all of the results for both applications independently and then together.

4.1.2 Pre-Experiment Questionnaire

The following sections present the analysis of the Pre-Experiment questionnaire completed by all participants of this experiment. A copy of this questionnaire can be found in Appendix B.

4.1.2.1 Demographics

A total of 23 subjects took part in this experiment, 7 females and 16 males. Due to a limited response from female participants and equipment failures, all data gathered for the female subjects was excluded from analysis. Out of the remaining participants, 14 subjects did not experience any equipment failures or other disturbances during

their sessions. To counterbalance properly, only 12 subjects were required, two from each of the experimental orders. Before analyzing any data, the decision was made to remove the last four subjects that participated to reduce the set of subjects to six pairs, one pair for each trial order. Of the remaining 12 participants, the mean age was 25.6 years of age with a standard deviation of 8.2 years. All of the participants were either in a degree program at the University of New Hampshire or had already completed a degree. Also, all of the remaining 12 participants were right handed.

In addition to the standard demographic information above, subjects were asked if they had interacted with the scroll wheel navigation methods such as the control interface for the iPod Classic (®). As anticipated, most of the subjects (8 out of 12) had used a circular iPod Classic's (®) touch interface.

4.1.2.2 Experience with Touch Screen Technology

Out of 12 participants, 11 had prior experience with touch screen interfaces and 9 indicated that they used a touch screens more than once a day at the time of the experiment. Question 10 of the pre-experiment questionnaire asked the subjects to indicate the frequency of use for a number of devices with touch screen interfaces. Table 4.1 shows the subject's responses for Question 10.

4.1.2.3 Experience with Mapping Software

As discussed in Chapter 3, the Mapping Application was designed to simulate a mapping application such as Google Maps (®), Google Earth(®) or Bing Maps(®). Subjects were asked to estimate their usage of different mapping software applications. All of the subjects indicated that they had some experience with mapping technologies and 8 subjects indicated that they used mapping software on a regular basis. Question 14 of the pre-experiment questionnaire asked the subjects who identified as regular

Device	More than once a day	Once a Day	A few times a week	Once a week	Less than once a week	I do not use touch on this device
Desktop Computer	0	0	0	0	0	9
Laptop Computer	1	0	1	0	1	6
Cell Phone / PDA	7	0	1	0	0	1
Tablet	1	0	0	0	2	6
Other (What)	0	0	1(Cash Register)	0	0	0

Table 4.1: The number of self identified “Regular Users” of touch screen interfaces that indicated each frequency of use for each type of touch screen device

users of mapping software, to indicate their frequency of use for different software mapping applications. Table 4.2 presents the responses for Question 14.

Software	More than once a day	Once a Day	A few times a week	Once a week	Less than once a week	I do not use this mapping software
Google Maps ®	0	1	3	3	1	0
Google Earth ®	0	0	0	1	7	0
Bing Maps ®	0	0	0	1	1	6
Virtual Earth ®	0	0	0	0	2	6
GIS	0	0	0	0	1	7
Other (What)	0	0	0	1 (In Car GPS)	0	0

Table 4.2: The number of self identified “Regular Users” of software mapping applications that indicated each frequency of use for each mapping software application.

Question 16 went further and asked the subjects if they had any experience with mapping software with touch interfaces. Five of the 12 subjects indicated that they had used touch based mapping software. Question 17 had the subjects select how often they used mapping software with touch interfaces on different types of devices. Table 4.3 shows the responses of Question 17.

Software	More than once a day	Once a Day	A few times a week	Once a week	Less than once a week	I do not use this mapping software
Desktop Computer	0	0	0	0	1	4
Laptop Computer	0	0	0	0	1	4
Cell Phone / PDA	0	0	1	2	1	1
Tablet	0	0	0	0	0	5
Other (What)	0	0	0	1(GPS)	1(iPad ®)	0

Table 4.3: The number of subjects who had used mapping software with touch screen technology for each frequency of use per touch screen device.

4.1.2.4 Experience with Tangible User Interfaces

The final section of the pre-experiment questionnaire was intended to gauge subjects experience with tangible user interfaces (TUI) when used as an input device for a computer. Ten of the subjects indicated they they had at least some experience with TUI computer input devices, but only four indicated that they used a TUI on a regular basis. Question 21 asked the self identified “Regular Users” of TUIs to indicate their frequency of use for a selected to TUIs. Table 4.4 shows the responses for Question 21.

Software	More than once a day	Once a Day	A few times a week	Once a week	Less than once a week	I do not use this device
Nintendo Wii ® Controller	0	0	0	0	5	0
Video Editing Puck	0	0	0	0	0	5
Other (What)	0	0	0	0	0	0

Table 4.4: The number of self identified “Regular Users” of TUIs that indicated each frequency of use for each TUI.

4.1.2.5 Analysis of Pre-Experiment Questionnaire

A majority of the participants for the Mapping Application experiment had some previous experience with touch screens, mapping software and tangible user interface and all had a basic understanding of their operation. The subject responses in Table 4.1 indicated that most participants familiarity with touch based interface come from experience with touch based cell phones and PDAs. Also, the results in Table 4.3 indicated that the most common category of device used to interact with mapping software was cellphones or PDAs for the participants of the Mapping Application experiment. While the results of the data gathered from the questions of the pre-experiment questionnaire were interesting, only a small subset of the subjects did not have any experience with the three technologies so analysis of the responses could not be reviewed as a factor in the data to follow.

4.1.3 NASA-TLX Assessments

Following each section of the Mapping Application experiment, the NASA-TLX assessment was administered in an attempt to estimate the cognitive load of the subject for each interface. Each assessment resulted in a single value that was collected for later analysis. Due to the subjective nature of the NASA-TLX assessment, the

values that resulted for each subject could not be compared directly between subjects. To account of the difference between subjects, a mean value was computed for each subject for all three assessments and the mean value was subtracted from each of the assessment results of that subject. The assessment results were arranged into two sets which were then analyzed. First, each value was sorted by the type of interface used. Second, each result was sorted by the order in which the sections were presented to test for an order effect.

After performing the repeated measures analysis in SPSS, neither a significant result nor a trend ($p \leq 0.15$) was found for either order of data. The null hypothesis of all differences in NASA-TLX assessment results being the same could not be rejected.

4.1.4 Blink Rate

Following the experiment, footage from the camera mounted to the display surface was reviewed. During the analysis of the first six subjects, it was determined that the rate which the subjects blinked usually less than once per task and in some cases, the blinks were faster than that camera could capture. Due to the sparse nature of this data, it was excluded from analysis.

4.1.5 Experiment Logging Data Review

The following sections will analyze a collection of metrics that were calculated by using the variables presented in Section 3.5.1, Table 3.10, Table 3.11, and Table 3.12. Each of the metrics covered will be introduced by describing its meaning to the experiment and its derivation. Next, the methods which were used for analyzing the metric will be discussed followed by the results of the analysis. Finally, the interpretation of the results will be presented.

4.1.5.1 Mean Overall Motion Time

4.1.5.1.1 Meaning and Derivation Mean overall motion time was selected to measure the length of time for which the subjects were interacting with each of the interfaces being tested. The mean overall motion time was computed by subtracting the time of the last movement of any interface for the given task from the first movement time for that task. This metric was selected to take the place of the full task time by excluding the time it took for the subject's hand to move from the start button to the interface.

4.1.5.1.2 Results The Surface Slider interface was significantly slower than the Physical Puck interface with a mean difference of 2.6 seconds ($p = 0.008$). The analysis also highlighted a possible trend that the the Surface Slider may have been slower than the Virtual Puck interfaces. The mean difference between the Surface Slider and Virtual Puck was 1.6 seconds ($p = 0.074$). If the Mapping Application experiment was conducted again and included more subjects the difference between the Surface Slider and the Virtual Puck may become significant. The results from the overall motion times by interface type is shown in Table 4.5.

Interface 1	Interface 2	Mean Difference (Seconds)
Surface Slider	Physical Puck	2.598 ($p = 0.008$)
Surface Slider	Virtual Puck	1.633 ($p = 0.074$)
Virtual Puck	Physical Puck	0.965 ($p = 0.404$)

Table 4.5: The mean difference of mean motion times between each interface type as well as the p value for each grouping.

4.1.5.1.3 Discussion The analysis above shows that there was a significant difference and a possible trend between the Surface Slider and the Physical Puck and the Virtual Puck respectively.

4.1.5.2 Mean Coarse Motion Time

4.1.5.2.1 Meaning and Derivation The mean coarse motion time represents the amount of time that a subject spent traversing the given data set while interacting with the coarse motion method for each interface. The mean coarse motion time was computed by summing the length of time for each of the coarse motion interactions of a given task. The time of a coarse motion interaction was the difference between the last and first movement for each coarse motion event. For each interface type, a mean coarse motion time was computed by averaging all coarse motion interaction times for each subject.

4.1.5.2.2 Results The repeated measures analysis by interface type resulted in two highly significant results and one possible trend. First, the null hypotheses that the coarse motion time for the Surface Slider and both the Physical, and Virtual Pucks were the same was rejected ($p < 0.0001$). In both cases, the Surface Slider's mean coarse motion time was more than 1 second longer for each task for each of the interfaces. The trend identified from the mean coarse motion time data was between the Physical and Virtual Puck interfaces, suggesting that the Physical Puck's coarse motion method may have been faster than the Virtual Puck's by almost a half second per task. Table 4.6 contains the results from the analysis of mean coarse motion time data.

Interface 1	Interface 2	Mean Difference (Seconds)
Surface Slider	Physical Puck	1.776 ($p < 0.0001$)
Surface Slider	Virtual Puck	1.343 ($p < 0.0001$)
Virtual Puck	Physical Puck	0.443 ($p = 0.119$)

Table 4.6: The mean difference of mean coarse motion times between each interface type as well as the p value for each result.

4.1.5.2.3 Discussion The analysis of mean coarse motion time data may have indicated that the shape of the coarse motion method for both the Physical and Virtual Puck interfaces had a significant effect on the length of time that the subjects interacted with the coarse motion portion of both interfaces. It was expected that all three coarse motion interfaces would have similar interaction lengths due the design considerations covered in Section 3.2.3.1.

4.1.5.3 Mean Coarse Motion Rate

4.1.5.3.1 Meaning and Derivation Mean coarse motion rate represents the mean number of values the subjects traversed per second when using the coarse motion control of a given interface. The mean coarse motion rate was computed by dividing the total number of points traversed with the coarse motion interface by the total time that the coarse motion control was in use for each task. The average number of points per second traversed for each task of a given interface were combined into one average for each interface type.

4.1.5.3.2 Results Repeated measures analysis of mean coarse motion rate data showed two significant results when grouped by interface type. Table 4.7 lists the the mean number of points traversed per second by the subjects with the coarse motion portion of each interface type. The results of the analysis are shown in Table 4.8. Two significant results were found. Both the Physical and Virtual puck interfaces had a significantly higher number of points traversed per second with 247.5 ($p = 0.002$) and 242.5 ($p = 0.003$) points per second faster respectively. No significant difference was found between the Virtual and Physical Puck's methods for coarse movement.

4.1.5.3.3 Discussion When designing and implementing the Mapping Application experiment, we expected that any significant difference would be found between the fine motion methods. The results from the mean coarse motion rate analysis indi-

Interface	Points Per Second	Standard Deviation (Points per second)
Surface Slider	567.6126	117.9598
Physical Puck	815.1952	204.67625
Virtual Puck	810.1829	246.79856

Table 4.7: The mean number of points per second traversed by subjects and the standard deviation for the coarse motion portion of each interface.

Interface 1	Interface 2	Mean Difference (Points per second)
Surface Slider	Physical Puck	-247.583 (p = 0.002)
Surface Slider	Virtual Puck	-242.570 (p = 0.003)
Virtual Puck	Physical Puck	-5.012 (p = 0.914)

Table 4.8: The mean difference of coarse motion rate between each interface type including the p value for each result.

cated that the linear slider and the semi-circular slider interfaces were not as similar as anticipated in the design of the interfaces.

4.1.5.4 Mean Fine Motion Time

4.1.5.4.1 Meaning and Derivation Mean fine motion time represents the amount of time that a subject was traversing the given data set while interacting with the fine motion method for each particular interface. Mean fine motion time was computed by summing the length of time taken for each of the fine motion interactions for a given task. The time of a fine motion interaction was the difference between the first and last movement for each fine motion event. For each interface type, a mean fine motion time was computed by averaging all interaction times for each task.

4.1.5.4.2 Results Repeated measures analysis by interface type resulted in no significant results. When designing the interfaces it was anticipated that a significant

result would exist between at least the Surface Slider and Physical Puck interfaces due to the drastic difference in design. Table 4.9 has a list of the mean times the standard deviations for each of the interfaces and Table 4.10 provides the results of the analysis done on the same data. While no significant differences were found a possible trend was identified between the Surface Slider and the Physical Puck where the Surface Slider took almost one second longer on average ($p = 0.115$).

Interface	Second	Standard Deviation (Second)
Surface Slider	11.234	3.080
Physical Puck	10.371	2.859
Virtual Puck	10.390	3.361

Table 4.9: The mean time standard deviation in seconds that the subjects interacted with the fine motion portion of the interface.

Interface 1	Interface 2	Mean Difference (Seconds)
Surface Slider	Physical Puck	0.863 ($p = 0.115$)
Surface Slider	Virtual Puck	0.844 ($p = 0.268$)
Virtual Puck	Physical Puck	0.019 ($p = 0.977$)

Table 4.10: The mean difference of fine motion times between each interface type including the p value for each result.

4.1.5.4.3 Discussion The mean fine motion time data showed no significant differences between the Surface Slider interface and both puck interfaces. A possible trend was found between the Physical Puck and the Surface Slider that could become significant if the experiment was rerun with more subjects or longer experiments.

4.1.5.5 Mean Fine Motion Rate

4.1.5.5.1 Meaning and Derivation Mean fine motion rate represents the mean number of values the subjects traversed per second when using the fine motion control of a given interface. Mean fine motion rate was computed by dividing the total number of points traversed with the fine motion control by the total time that the fine motion control was in use for each task. The average number of points per second traversed for each task of a given interface were combined into one average for each interface type.

4.1.5.5.2 Results The repeated measures analysis of the mean fine motion rate data showed two significant results when ordered by interface type. Table 4.11 lists the the mean number of points traversed per second for each fine motion control method of each interface type. The results of the analysis is shown in Table 4.12. Both the Physical and Virtual Puck interfaces had a significantly higher traversal rate of 15.06 ($p = 0.001$) and 10.75 ($p < 0.001$) points per second respectively when compared to the Surface Slider interface. No significant difference was found between the fine motion control methods Virtual and Physical Puck's interfaces.

Interface	Points Per Second	Standard Deviation
Surface Slider	16.390	2.339
Physical Puck	31.449	9.979
Virtual Puck	32.184	6.124

Table 4.11: The mean number of points per second traversed and the standard deviation for the fine motion portion of each user interface.

4.1.5.5.3 Discussion As anticipated, the Surface Slider interface had a lower number of points traversed per second when compared to the Physical Puck interface. It was also expected that the Physical Puck would have had significantly higher

Interface 1	Interface 2	Mean Difference (Points per second)
Surface Slider	Physical Puck	-15.059 ($p = 0.001$)
Surface Slider	Virtual Puck	-15.749 ($p < 0.001$)
Virtual Puck	Physical Puck	0.735 ($p = 0.821$)

Table 4.12: The mean difference of fine motion rate between each interface type including the p value for each result.

traversal rate than the Virtual Puck, but no significant difference was found. The results from the mean fine motion rate analysis suggest that the style of the fine control interface has more of an effect on the traversal rate than the interface being a physical object or a virtual control.

4.1.5.6 Mean Transition Time

4.1.5.6.1 Meaning and Derivation Mean transition time was intended to measure how quickly the subjects switched from one control method to another during a task. A shorter transition time may have been an indicator that an interface was more intuitive to use or that the interface was easier to use. The transition time of for each interface was defined as the time between a subject's last movement with the coarse motion control to the first movement of the fine motion control or from the last motion of the fine motion control to the first motion of the coarse motion control. The mean transition time metric could only be calculated if the subject used both control methods for the task otherwise the given task was excluded from the following analysis. If multiple transitions occurred, the times for each transition were averaged to create one value per task. All transition time's for a subject for a given interface were averaged resulting in three mean transition time values per subject.

4.1.5.6.2 Results Repeated measures analysis of mean transition time data showed not significant results. Table 4.13 contains the mean transition times as well as the

standard deviation for each interface type. Table 4.14 contains the results of the analysis for the mean transition time metric.

Interface	Second	Standard Deviation (Seconds)
Surface Slider	0.873	0.656
Physical Puck	1.020	0.249
Virtual Puck	1.080	0.507

Table 4.13: The mean and the standard deviation in seconds of the mean transition times for each of the interface types.

Interface 1	Interface 2	Mean Difference (Second)
Surface Slider	Physical Puck	0.21 (p =0.499)
Surface Slider	Virtual Puck	0.209 (p = 0.344)
Virtual Puck	Physical Puck	0.125 (p = 0.64)

Table 4.14: The mean difference between the mean transition times in seconds for each interface type including the p value for each result.

4.1.5.6.3 Discussion As expected, the null hypothesis that the mean transitions times were the same could not be rejected. While the analysis cannot show that the mean transition time is the same, no significance at this scale indicated that the the transition time was not a major factor in the task completion times.

4.1.5.7 Mean Heart Rate Standard Deviation

4.1.5.7.1 Meaning and Derivation A common metric used in many other experiments is known as heart rate variability. Heart rate variability uses spectral analysis of the raw heart rate signal over different periods of time from 1 minute up to 20 minutes. Due to the short nature of the tasks for the Mapping Application

experiment and the noise present in many signals, heart rate variability analysis was not feasible. In place of heart rate variability, the mean heart rate standard deviation was computed for each input method. Each task had a periodic instantaneous heart rate measurement computed from the heart rate data logging. The data from the instantaneous heart rate was used to compute a standard deviation for each task. A mean of the standard deviations for all tasks with one interface was computed for each subject. The three mean standard deviations from each subject were then used for the analysis to follow. Mean heart rate standard deviation metric was intended to represent how much the subject's heart rate fluctuated through the tasks and as a substitute for heart rate variability.

4.1.5.7.2 Results Table 4.15 shows the computed values for the mean heart rate standard deviation by interface type and the standard deviation of the mean standard deviations for each task. Table 4.16 shows the results of the repeated measures analysis on the computed data. No significant results were found when analyzing the mean heart rate standard deviation data but a possible trend was found between the mean heart rate standard deviations of the Surface Slider and the Virtual Puck.

Interface	Mean Standard Deviation (Beats Per Minute)	Standard Deviation (Beats Per Minute)
Surface Slider	3.885	1.704
Physical Puck	3.467	1.240
Virtual Puck	3.464	1.243

Table 4.15: The mean standard deviation and standard deviation of the mean standard deviation heart rate by interface type in Beats Per Minute.

4.1.5.7.3 Discussion The EKG signals for the Mapping Application experiment contained more noise than expected before the experiment. As a result of the noise, and the short nature of each task, the heart rate variability measurement which was

Interface 1	Interface 2	Mean Difference (Beats Per Minute)
Surface Slider	Physical Puck	0.418 (p = 0.185)
Surface Slider	Virtual Puck	0.312 (p = 0.124)
Virtual Puck	Physical Puck	0.26 (p = 0.699)

Table 4.16: The mean difference between the mean standard deviation of the heart rates for each task (in beats per minute) by interface type including the p value for each result.

desired could not be calculated. Our simplification of this metric did not have any significant results but had one possible trend between the Surface Slider and the Virtual Puck. The possible trend could be examined in later work.

4.1.5.8 Mean Skin Conductance

4.1.5.8.1 Meaning and Derivation Ikehara et al. showed that skin conductance can be an estimate of cognitive load for a task[11]. The skin conductance of the subjects was measured throughout each task and an average value in microsiemens was computed. The mean skin conductance for each task was averaged to create the mean skin conductance for each interface type. The three values from each subject were used in the analysis to follow.

4.1.5.8.2 Results Table 4.17 shows the mean and standard deviation of the mean skin conductance for each interface type. Table 4.18 contains the results from repeated measures analysis of the mean skin conductance data. Analysis found no significant results, but one possible trend was identified between the Surface Slider and Virtual Puck, suggesting the subjects may have a lower skin conductance when using the Surface Slider interface.

Interface	Mean Skin Conductance (microsiemens)	Standard Deviation (microsiemens)
Surface Slider	4.732	1.688
Physical Puck	4.808	1.643
Virtual Puck	4.968	1.580

Table 4.17: The mean and standard deviation of the mean skin conductance for each interface measured in microsiemens.

Interface 1	Interface 2	Mean Difference (microsiemens)
Surface Slider	Physical Puck	-0.076 (p = 0.755)
Surface Slider	Virtual Puck	-0.236 (p = 0.134)
Virtual Puck	Physical Puck	0.222 (p = 0.489)

Table 4.18: The mean difference between the mean skin conductance (in microsiemens) for each interface type including the p value for each result.

4.1.5.8.3 Discussion The possible trend of lower mean skin conductance for users interacting with the Surface Slider when compared to the Virtual Puck could suggest that the Surface Slider required less cognitive load than the Virtual Puck [16]. More data from an extended experiment could decrease the p value for the mean skin conductance test and possible lead to a significant result. The absence of significant results suggest that the mean skin conductance method of cognitive load estimation was not suitable for the Mapping Application experiment or the difference, if any, between the interface types was negligible.

4.1.6 Post-Experiment Questionnaire

The following sections present the analysis of the Post-Experiment questionnaire completed by all participants. A copy of this questionnaire can be found in Appendix E. All but questions 5 and 6 were presented as a five point Likert scale. The points on the scale for all Likert scale questions were Strongly Disagree, Disagree, Neither agree

nor disagree, Agree and Strongly Agree. Ordinal values of 1 through 5 were assigned to each of the options with 1 being Strongly Disagree and 5 being Strongly Agree. The mean value for all responses was computed using ordinal values as described. For the remaining two questions, subjects were asked to rank the three interfaces with 1 being the most favorable and and 3 being the least. The following sections will review the results of the questionnaire grouped as they were in the questionnaire.

4.1.6.1 Experiment Instructions

The first set of questions after the experiment were intended to gauge how well the recorded instructions were conveyed to the subjects before the experiment. Table 4.19 has a breakdown of the participant responses for Question 1. The mean of the responses computed for question 1 was a 4.42, indicating that, on average, the subjects agreed with the statement “The instructions at the beginning of the experiment were clear.”

Option	Number of participants
Strongly Disagree	0
Disagree	1
Neither agree nor disagree	0
Agree	7
Strongly Agree	4

Table 4.19: Participant responses to Question 1, “The instructions at the beginning of the experiment were clear.”

Questions 2, 3, and 4 asked the subject to indicate their level of agreement with the statements “The instructions at the beginning of the X interface section were clear”, where X was replaced with Surface Slider, Virtual Puck, and Physical Puck. Tables 4.20, 4.21, and 4.22 have the breakdown of subject responses for the Surface Slider, Virtual Puck and Physical Puck respectively. The mean response for all

three statements across all subjects was 4.25 indicating that subjects agreed that the instructions before each interface were clear.

Option	Number of participants
Strongly Disagree	0
Disagree	0
Neither agree nor disagree	0
Agree	9
Strongly Agree	3

Table 4.20: Participant responses to Question 2, “The instructions at the beginning of the Surface Slider portion were clear.”

Option	Number of participants
Strongly Disagree	0
Disagree	0
Neither agree nor disagree	0
Agree	9
Strongly Agree	3

Table 4.21: Participant responses to Question 3, “The instructions at the beginning of the Virtual Puck portion were clear.”

Option	Number of participants
Strongly Disagree	0
Disagree	0
Neither agree nor disagree	0
Agree	9
Strongly Agree	3

Table 4.22: Participant responses to Question 4, “The instructions at the beginning of the Physical Puck portion were clear.”

4.1.6.2 Overall Questions

In the following two questions, the subjects were asked to rank the interfaces, from 1 to 3, 1 being the most favorable to 3 being the least favorable. First, the subjects were asked to rank the interfaces in order of their preference for the Mapping Application experiment. Table 4.23 contains the collated responses from all of the subjects. Means were computed by summing the rank for each interface across all subjects and dividing by the total number of subjects to impose it on an artificial gradient. The Surface Slider interface's mean was 2.17 and both puck interfaces had a mean value of 1.92. These results suggest that subjects preferred using both of the puck based interfaces to the Surface Slider.

Option	First Choice	Second Choice	Third Choice
Surface Slider	2	6	4
Virtual Puck	5	3	4
Physical Puck	5	3	4

Table 4.23: Participant responses to Question 5, "Please rank each of the interfaces based on which you would prefer to use with 1 being the highest preference and 3 being the lowest."

Next, the subjects were asked to rank the interfaces by which they thought was fastest method to find the answer for the given tasks. Table 4.24 contains the collated responses from all of the subjects. Using the same method as previously described, the means for each interface were computed. The Physical Puck had the lowest mean overall with 1.75 followed by the Virtual Puck with 2.0 and finally the Surface slider with 2.25. These results indicated that on average, subjects perceived that the Physical Puck was the fastest interface to use out of the three provided and the Surface Slider was the slowest.

The final portion of the questions relating to the full experiment asked subjects if they would be more likely to try an application if the application made use of physical

Option	First Choice	Second Choice	Third Choice
Surface Slider	2	5	5
Virtual Puck	4	4	4
Physical Puck	6	3	3

Table 4.24: Participant responses to Question 6, “Please rank each of the interfaces based on how fast you were able to find the data of interest with 1 being the fastest interface and 3 being the slowest.”

objects as an input method. The breakdown of responses can be seen in Table 4.25. The mean response for this question was 2.83 or “Neither agree nor disagree”. An average response of “Neither agree nor disagree” indicated that subjects who have used the Physical Puck interfaces will probably not be drawn to applications that have similar interfaces.

Option	Number of participants
Strongly Disagree	1
Disagree	4
Neither agree nor disagree	4
Agree	2
Strongly Agree	1

Table 4.25: Participant responses to Question 7, “I would be more likely to use an application if it had tangible (physical) objects to interact with, such as the puck.”

4.1.6.3 Surface Slider Interface Review

The first question in Surface Slider interface review and the following two sections was intended to gauge if subjects understood how to properly operate the user interfaces after the instructions. The first questions of this and the following two sections also served as an integrity check to ensure that the subjects were answering the questions consistently. To verify the integrity, the mean response of the first question was compared to Question 2. It was assumed that Question 8 and Question 2 were

similar and would have a similar mean. The results for Question 2 are presented in Table 4.26. The mean for Question 2 was 4.67, indicating that the average subject strongly agreed that they understood how to find the answer for each question. The mean of Question 2, 4.75, was very close to the mean of Question 8 suggesting that the subjects were filling out the questionnaire consistently up to Question 8 point. The responses were deemed consistent if there was not more than one point difference. The individual responses from Questions 2 and 8 were consistent within each subject's questionnaire as well.

Option	Number of participants
Strongly Disagree	0
Disagree	0
Neither agree nor disagree	0
Agree	4
Strongly Agree	8

Table 4.26: Participant responses to Question 8, "I understood how to find the answer for each question."

The next question in the interface review sections asked the subject how well the interface responded to their movements. Table 4.27 contains the results from Question 9. The mean response for Question 9 of 3.75 suggested that the interface responded as the subject expected it would.

Option	Number of participants
Strongly Disagree	0
Disagree	2
Neither agree nor disagree	0
Agree	9
Strongly Agree	1

Table 4.27: Participant responses to Question 9, "The interface responded to my movements as I anticipated."

The final two questions for each interface review sections were intended to gauge how easy the subjects thought the interface was to use and how fun they considered the interface to be. The Surface Slider’s mean rating for the final two questions were 3.83 and 2.67 respectively. The mean values for questions 10 and 11 indicated that the average subject agreed that the Surface Slider was easy to use and neither agreed nor disagreed that the interface was fun to use. Table 4.28 and Table 4.29 contain the breakdown of the responses for Questions 10 and 11 respectively.

Option	Number of participants
Strongly Disagree	0
Disagree	1
Neither agree nor disagree	3
Agree	5
Strongly Agree	3

Table 4.28: Participant responses to Question 10, “The interface was easy to use.”

Option	Number of participants
Strongly Disagree	0
Disagree	6
Neither agree nor disagree	4
Agree	2
Strongly Agree	0

Table 4.29: Participant responses to Question 11, “The interface was fun to use.”

4.1.6.4 Virtual Puck Interface Review

Like the Surface Slider, Question 12 indicated that when subjects were interacting with the Virtual Puck interface strongly agreed that they understood how to find each answer for the tasks with an average response of 4.58. Table 4.30 contains the breakdown of all responses for Question 12. The integrity check done for the Surface

Slider interface was also done for this interface. The mean response for Questions 12 and Question 3 were both similar suggesting that the subjects were still consistent with their responses for this section also.

Option	Number of participants
Strongly Disagree	0
Disagree	0
Neither agree nor disagree	0
Agree	5
Strongly Agree	7

Table 4.30: Participant responses to Question 12, “I understood how to find the answer for each question.”

Question 13 asked the subjects if the Surface Slider responded as they had anticipated. Table 4.31 contains the results from Question 13. The mean response for Question 9 of 3.67 suggested that the interface responded as expected.

Option	Number of participants
Strongly Disagree	0
Disagree	1
Neither agree nor disagree	4
Agree	5
Strongly Agree	2

Table 4.31: Participant responses to Question 13, “The interface responded to my movements as I anticipated.”

The average response for both “The interface was easy to use” and “The interface was fun to use”, Questions 14 and 15, were 3.75 and 3.5 respectively. Both values indicate that the subjects agreed that the interface was fun and easy to use. Table 4.32 and Table 4.33 contain the responses for all of the subjects for each rating.

Option	Number of participants
Strongly Disagree	0
Disagree	1
Neither agree nor disagree	2
Agree	8
Strongly Agree	1

Table 4.32: Participant responses to Question 14, “The interface was easy to use.”

Option	Number of participants
Strongly Disagree	0
Disagree	1
Neither agree nor disagree	4
Agree	7
Strongly Agree	0

Table 4.33: Participant responses to Question 15, “The interface was fun to use.”

4.1.6.5 Physical Puck Interface Review

Similar to previous two interfaces, Question 16 had a mean response of 4.67 indicating that the subjects strongly agreed that they understood how to find the answers for each task. Table 4.34 has a breakdown of the responses for Question 16. The same consistency check done for the the other two interface reviews was also done for the Physical Puck interface. The mean response for Questions 16 and Question 4 were both similar suggesting that the subjects were still consistent with their responses.

The remaining three question for the Physical Puck interface had a higher average rating than the previous two interfaces. First, subjects agreed more strongly with the statement “The interface responded to my movements as I anticipated” with an average of 4.25, 0.5 higher than the next lowest. Two possible explanations for the higher rating could be related to the use of a physical object as part of the interface or having the physical object may have made the interface more predictable by not

Option	Number of participants
Strongly Disagree	0
Disagree	0
Neither agree nor disagree	0
Agree	4
Strongly Agree	8

Table 4.34: Participant responses to Question 16, “I understood how to find the answer for each question.”

requiring the subject to pay attention to the interface as much. Subjects also agreed that the Physical Puck interface was easy and fun to use with average ratings of 3.92 and 3.75 respectively. The responses for questions 17 through 19 can be found in Tables 4.35, Table 4.36 and Table 4.37.

Option	Number of participants
Strongly Disagree	0
Disagree	1
Neither agree nor disagree	2
Agree	2
Strongly Agree	7

Table 4.35: Participant responses to Question 17, “The interface responded to my movements as I anticipated.”

Option	Number of participants
Strongly Disagree	0
Disagree	3
Neither agree nor disagree	0
Agree	4
Strongly Agree	5

Table 4.36: Participant responses to Question 18, “The interface was easy to use.”

Option	Number of participants
Strongly Disagree	1
Disagree	2
Neither agree nor disagree	0
Agree	5
Strongly Agree	4

Table 4.37: Participant responses to Question 19, “The interface was fun to use.”

4.1.6.6 Comments

The last section of the post experiment questionnaire was an area for the subject to leave any last comments that they may have had. Two areas for improvement were identified by multiple subjects. First, when using the Virtual Puck interface, some subject’s fingers moved outside the grey circle or crossed over the black dot in the center. If the subject’s finger went outside the circle and touched the scrubber interface the current selected value would jump to the location touched on the scrubber. A related error occurred when the subject crossed the center point of the interface. Crossing the center point of the interface resulted in the application registering 180 degree rotation in an unknown direction (forward or backward in time). Both issues were not well known before the experiment but some controls could be added to reduce their effect in later works.

The second set of suggestions were related to improving the user experience with the Physical Puck interface. Two subjects suggested that the height of the puck be reduced to make the scrubber easier to see. Cutting the puck in half or fabricating another object could resolve the issue with the height of the puck. Two other subjects indicated that the rotation point of the puck was not ideal and should be engineered to be at the center of the puck. The pivot point for the Mapping Application experiment was slightly off center which resulted in the puck wobbling. Like the last suggestions, the puck wobbling could be resolved by manufacturing the interaction

device or further alterations to the existing device. Both sets of changes should be possible if either interface is used for later experiments but were not predicted before this experiment began.

4.2 Numbers Application

4.2.1 Summary

Sections 3.5.3 and 3.5.4 list the information that was gathered for the Numbers Application pilot experiment. The following sections will review the analysis of the data gathered during the Numbers Application pilot experiment. All subjects who took part in the Numbers Application pilot had some previous experience with the Microsoft Surface and the three interfaces being tested.

4.2.2 Eye Tracking Data Review

4.2.2.1 Summary

Throughout each run of Numbers Application pilot, an eye tracking system was used to measure the diameter of the subject's pupils. More information about the setup for the eye tracking system can be found in Section 3.4.2.3. Preliminary analysis of the data gathered with the eye tracker showed that only 5 out of the 14 participants had valid eye tracking data for more than 10% of their session. The remaining 9 subjects were excluded from the following analysis. Of the 5 valid subjects, only the left eye had valid tracking for more than 25% of the time for each section of the experiment. A total of 180 tasks were completed by the 5 participants (12 tasks for each interface and three interfaces per user). For the reasons described above, only the left eye tracking data was used in the analysis below.

4.2.2.2 Results

Table 4.38 shows the mean pupil diameter of the subjects for each interface type. The mean pupil diameter for each task was computed by averaging each valid pupil diameter measurement for a task to get a single value. All mean pupil diameter measurements for each interface type were averaged together to compute a single mean pupil diameter per subject per interface type. The standard deviation of the mean pupil diameters for each interface type is also included in the same table. Table 4.39 contains the results from the repeated measures analysis of the mean pupil diameters. One significant result was found as well as one possible trend. A mean difference of 0.217 mm ($p=0.019$) found between the mean pupil diameter of the subjects using the Surface Slider and the Virtual Puck interfaces. The larger mean pupil diameter of the subjects interacting with the Virtual Puck interface suggests that the Virtual Puck interface imparts higher cognitive load than the Surface Slider interface. Similarly, there was a mean difference of 0.338 mm ($p=0.133$) between the pupil diameters of subjects interacting with the Virtual Puck and the Physical Puck interfaces. The larger mean pupil diameter for subjects interacting with the Virtual Puck interface suggests a possible trend in higher cognitive load when compared to the Physical Puck interface. While the mean difference between the Virtual Puck and the Physical puck interfaces was larger, the finding was not significant.

Ordering the mean pupil diameter data by the presentation order for the subject resulted in no significant findings suggesting that no order effect was present for mean pupil diameter metric.

4.2.2.3 Discussion

The mean pupil diameter data was only valid for 5 of the 12 total subjects which prevented proper counterbalancing. No order effect was found when the repeated measures analysis was done for presentation order rather than interface type. Re-

Interface	Mean Diameter (mm)	Standard Deviation
Surface Slider	4.89	0.351
Physical Puck	4.67	0.282
Virtual Puck	5.01	0.522

Table 4.38: The mean diameter of the left eye pupil ordered by interface type.

Interface 1	Interface 2	Mean Difference (mm)
Surface Slider	Virtual Puck	-0.121 (p = 0.571)
Surface Slider	Physical Puck	0.217 (p = 0.019)
Physical Puck	Virtual Puck	0.338 (p = 0.133)

Table 4.39: The mean difference between the mean left eye pupil diameter (in millimeters) for each interface type including the p value for each result

peated measures analysis of the data grouped by interface type showed that the subjects were more cognitively loaded when using the Physical Puck interface when compared to the Surface Slider interface. A possible trend was also found suggesting that subjects were less cognitively loaded when interacting with the Physical Puck interface when compared to the Virtual Puck Interface.

4.2.3 Experiment Logging Data Review

4.2.3.1 Mean Total Task Time

4.2.3.1.1 Meaning and Derivation The total task time was the time in seconds from when the subject pressed the start button until they had pressed the stop button after finding the correct value. The tasks when the subject pressed the stop button while an incorrect value was selected were excluded from the following analysis. Mean total task time was intended to measure how long the subject took to complete a task with the given interface including any extra time to transition between the buttons and the interface being tested.

4.2.3.1.2 Results The mean task completion time and standard deviation can be found in Table 4.40. The analysis of mean total task time data, shown Table 4.41, indicated that the Physical Puck was significantly faster than both the Virtual Puck or the Surface Slider interfaces. No significant difference was found between the Surface Slider and Virtual Puck.

Interface	Mean (Seconds)	Standard Deviation (Seconds)
Surface Slider	14.177	3.21
Physical Puck	11.2372	1.35
Virtual Puck	14.1766	2.45

Table 4.40: The mean completion time and standard deviation to complete the task in seconds for each interface type.

Interface 1	Interface 2	Mean Difference (Seconds)
Surface Slider	Physical Puck	1.894 ($p = 0.019$)
Surface Slider	Virtual Puck	-1.045 ($p = 0.246$)
Virtual Puck	Physical Puck	2.939 ($p \leq 0.001$)

Table 4.41: The mean difference between the mean completion time for each task (in seconds) sorted by interface type including the p value for each result.

4.2.3.1.3 Discussion The mean total task time metric indicated that the Virtual Puck and the Surface Slider interfaces were slower to use than the Physical Puck interface for the Numbers Application. Mean total task time was not enough to state that the two interfaces are faster for all possible uses.

4.2.3.2 Mean In-motion Time

4.2.3.2.1 Meaning and Derivation The mean in-motion time for each interface was computed by summing the difference in start time and the stop time for each

interaction with the fine or coarse motion portion of the given interface. Mean in-motion time was able to exclude the time before the first movement and after the last movement as well as the time while the subject was transitioning from coarse motion to fine motion or from fine motion to coarse motion. Due to limitations of the input device, it was not possible to exclude time when the subject paused and then returned to the same method of interaction.

4.2.3.2.2 Results Table 4.42 contains the mean in-motion time for each interface in seconds as well as the standard deviation for each of the times. Table 4.43 shows the results of the repeated measures analysis of mean in-motion time. Two significant results were found from the mean in-motion time data. The subjects spent more time interacting with the Virtual Puck and the Surface Slider interfaces than with the Physical Puck interface. Also, no significant difference was found between the Virtual Puck and the Surface Slider interfaces.

Interface	Mean (Seconds)	Standard Deviation (Seconds)
Surface Slider	11.816	3.20
Physical Puck	9.558	1.40
Virtual Puck	12.5434	2.42

Table 4.42: The mean in motion time and standard deviation to complete the task in seconds for each interface type.

4.2.3.2.3 Discussion Analysis of mean in-motion time revealed that the subjects took significantly more time to interact with the Surface Slider and the Virtual Puck interfaces than with the Physical Puck interface. With more testing, a difference could possibly be found between the Surface Slider and Virtual Puck interfaces but it was not present in the Numbers Application pilot.

Interface 1	Interface 2	Mean Difference (Seconds)
Surface Slider	Physical Puck	2.258 (p = 0.008)
Surface Slider	Virtual Puck	-0.727(p = 0.411)
Virtual Puck	Physical Puck	2.985 (p <= 0.001)

Table 4.43: The mean difference between the mean in motion time for each task (in seconds) sorted by interface type including the p value for each result.

4.2.3.3 Mean Coarse Motion Time

4.2.3.3.1 Meaning and Derivation The mean coarse motion time was computed by taking the difference between the first and last motion times of each interaction with the coarse motion method for each interface. In the event that the subject interacted with the coarse motion interface more than once for a task, each of the individual times were summed to create a total coarse motion time for that task. The coarse motion times for each task were averaged for all tasks with a given interface to create one value per interface per subject. Mean coarse motion time was intended to measure how long the average interaction with the coarse motion portion of the given interface was for each of the different interfaces.

4.2.3.3.2 Results Table 4.44 has the average time in seconds and the standard deviation of for the coarse motion time for each interface. The results of the repeated measures analysis can be found in Table 4.45. Significant results were found between each pair of interfaces. The Physical Puck's coarse motion interface had the lowest mean interaction time with of 3.63 seconds followed by the Virtual Puck's mean time of 5.35 seconds and finally the Surface Slider had the longest mean time of 6.33 seconds.

4.2.3.3.3 Discussion Mean coarse motion time showed that the subjects spent less time with the puck interfaces than the Surface Slider. The results from the

Interface	Mean (Seconds)	Standard Deviation (Seconds)
Surface Slider	6.33	1.49
Physical Puck	3.63	1.40
Virtual Puck	5.35	1.77

Table 4.44: The mean coarse motion time and standard deviation for each task in seconds for each interface type.

Interface 1	Interface 2	Mean Difference (Seconds)
Surface Slider	Physical Puck	2.698 ($p \leq 0.001$)
Surface Slider	Virtual Puck	0.975 ($p = 0.026$)
Virtual Puck	Physical Puck	1.723 ($p = 0.001$)

Table 4.45: The mean difference between the mean coarse motion time for each task (in seconds) sorted by interface type including the p value for each result.

analysis of mean coarse motion time could possibly indicate that the subjects preferred the fine motion interface provided by the puck interfaces or they could have disliked the coarse motion interface for the pucks and elected to use the fine motion control for longer.

4.2.3.4 Mean Fine Motion Time

4.2.3.4.1 Meaning and Derivation Similar to the mean coarse motion time metric in Section 4.2.3.3, the mean fine motion time metric measured how long the subjects were interacting with the fine motion portion of each interface. The derivation methods were the same for mean fine motion time metric as they were for the mean coarse motion time using the fine motion portion of the interfaces in place of the coarse motion portion.

4.2.3.4.2 Results Table 4.46 contains the mean and standard deviation of the subjects fine motion interaction durations for each of the interfaces. Table 4.47 contains the results from the repeated measures analysis of the data set. Two significant results were found in the analysis of the mean fine motions time data. First, the mean difference between the Virtual Puck and the Surface Slider interfaces was 2.03 seconds ($p = 0.021$). The other significant result found was between the Virtual Puck and the Physical Puck interfaces. A mean difference of 1.24 seconds ($p = 0.025$) indicated that the Virtual Puck was also slower than the Physical Puck. No significant result was found between the Surface Slider and the Physical Puck.

Interface	Mean (Seconds)	Standard Deviation (Seconds)
Surface Slider	6.79	3.09
Physical Puck	7.57	1.72
Virtual Puck	8.82	1.48

Table 4.46: The mean fine motion time and standard deviation for each task in seconds for each interface type.

Interface 1	Interface 2	Mean Difference (Seconds)
Surface Slider	Physical Puck	-0.79 ($p = 0.22$)
Surface Slider	Virtual Puck	-2.03 ($p = 0.021$)
Virtual Puck	Physical Puck	1.24 ($p = 0.025$)

Table 4.47: The mean difference between the mean fine motion time for each task (in seconds) sorted by interface type including the p value for each result.

4.2.3.4.3 Discussion The analysis of the mean fine motion time indicated that the fine motion portion of the Virtual Puck interface was used for a significantly longer amount of time than the fine motion interfaces on the other two interfaces.

One possible explanation of the significant difference between the Virtual Puck and the other two interfaces could be attributed to the users preferring the fine motion interface to the coarse motion interface of the Virtual Puck or the users the users may have preferred the coarse motion interface on the other interfaces.

4.2.3.5 Mean Coarse Motion Traversal Rate

4.2.3.5.1 Meaning and Derivation Mean coarse motion traversal rate represented the number of values the subjects traversed per second when using the coarse motion portion of the given interface. Mean coarse motion traversal rate was computed by dividing the total number of points traversed with the coarse motion interface by the total time that the that the coarse motion interface was in use. Mean coarse motion traversal rate metric was intended to measure how quickly the subjects interacted with the coarse motion portion for the given interface.

4.2.3.5.2 Results Table 4.48 contains the mean coarse motion traversal rate and standard deviation listed by interface type. Table 4.49 contains the results of the repeated measures analysis of the mean coarse motion traversal rate data and showed one significant result in addition to one possible trend. First, the mean difference between the Physical Puck and the Surface Slider was 265.82 points per second ($p=0.075$), indicating a possible trend that the Surface Slider's coarse motion traversal rate was slower than the Physical Puck's coarse motion traversal rate. The significant result found was between the Virtual Puck and the Surface Slider. The mean difference between the Virtual Puck and the Surface Slider was 189.25 points per second ($p=0.034$), indicating that the Virtual Puck had a faster coarse motion traversal rate when compared to the Surface Slider.

4.2.3.5.3 Discussion The mean coarse motion traversal rate of the Surface Slider was significantly slower than the Virtual Puck possibly indicating a preference for the

Interface	Mean (Points Per Seconds)	Standard Deviation (Points Per Seconds)
Surface Slider	319.90	204.97
Physical Puck	1294.23	1687.85
Virtual Puck	695.09	442.75

Table 4.48: The mean coarse motion traversal rate and standard deviation for each task in points per second for each interface type.

Interface 1	Interface 2	Mean Difference (Points Per Seconds)
Surface Slider	Physical Puck	-265.82 (p = 0.075)
Surface Slider	Virtual Puck	-189.25 (p = 0.034)
Virtual Puck	Physical Puck	-76.57 (p = 0.66)

Table 4.49: The mean difference between the mean coarse motion traversal time for each task (in points per second) sorted by interface type including the p value for each result.

Surface Slider's coarse motion control or a dislike of the coarse motion interface for the Virtual Puck. The possible trend the the Surface Slider was slower than the Physical Puck could become more concrete if more data was available from a longer experiment or more tasks.

4.2.3.6 Mean Fine Motion Traversal Rate

4.2.3.6.1 Meaning and Derivation Mean fine motion traversal rate represented the number of values the subjects traversed per second with the fine motion portion of the given interface. This metric was computed by dividing the total number of points traversed using the fine motion portion of the interface by the total time that the fine motion portion of the interface was in use. Mean fine motion traversal rate was intended to measure how quickly the subjects could interact with the fine motion portion of a given interface.

4.2.3.6.2 Results Table 4.50 contains the mean fine motion traversal rate and standard deviation for each interface. Table 4.51 contains the results of the repeated measures analysis of the mean fine motion traversal rates for each interface. One significant result and one possible trend was identified. The mean difference between the Physical Puck's mean fine motion interface traversal rate and the mean fine motion traversal rate of the Surface Slider was -3.82 points per second with $p=0.002$. The significant difference between the Physical Puck and the Surface Slider suggested that the Physical Puck allowed subjects to traverse the data more quickly than they could with the Surface Slider interface. A similar result was found between the Virtual Puck and the Surface Slider interfaces with a mean difference was 1.93 points per second with $p=0.126$, while not significant this result is a possible trend.

Interface	Mean (Points Per Seconds)	Standard Deviation (Points Per Seconds)
Surface Slider	8.53	3.22
Physical Puck	12.36	4.84
Virtual Puck	10.46	3.03

Table 4.50: The mean mean fine motion traversal rate and standard deviation for each task in points per second for each interface type.

Interface 1	Interface 2	Mean Difference (Points per second)
Surface Slider	Physical Puck	-3.82 ($p = 0.002$)
Surface Slider	Virtual Puck	-1.93 ($p = 0.126$)
Virtual Puck	Physical Puck	-1.90 ($p = 0.217$)

Table 4.51: The mean difference between the mean mean fine motion traversal time for each task (in points per second) sorted by interface type including the p value for each result.

4.2.3.6.3 Discussion The traversal rate of the fine motion control portion of the Physical Puck interface was significantly faster than the fine motion control portion of the Surface Slider interface. A similar but not significant result was found between the Virtual Puck and the Surface Slider when the Virtual Puck may have had a faster traversal rate. The possible trend suggested that the Virtual Puck interface's fine motion control interface may be faster at traversing the data compared to the Surface Slider but, this result was not significant.

4.2.4 Post-Experiment Ranking Review

After the subjects had completed all three sections of the experiment, they were asked to rank the three interfaces, once for preference and once for which they thought was the fastest to interact with. Table 4.52 contains the responses ranking each of the interfaces in order of preference. For the Numbers Application pilot experiment, 10 of the 12 subjects indicated that the Physical Puck was their interface of choice, ranking it as their most preferred interface. Analysis similar to Section 4.1.6.2, was performed on the user preference data by computing an average rating for all three interfaces. Each of the responses given was assigned a point value from 1 being the "Most Preferred" to 3 being the "Least Preferred". Interfaces that had a lower average rating were more preferred than interfaces with a higher average rating. The final column of the preference rating table shows the mean computed using the method described. The averages showed that the Physical Puck was preferred over both the Surface Slider and the Virtual Puck interfaces. The Surface Slider and the Virtual Puck had no difference in average rating for the Numbers Application pilot experiment.

Table 4.53 contains the subject responses for which interface the subjects felt was the fastest for the given tasks. With very similar results to the previous question, the Physical Puck was rated as the fastest by 10 out of the 12 subjects. The only difference between the rankings for the fastest interface and the most preferred was

Option	Most Preferred	Neutral Preference	Least Preferred	Average
Surface Slider	1	5	6	2.41
Virtual Puck	1	5	6	2.41
Physical Puck	10	2	0	1.17

Table 4.52: Participant responses when asked to rank interfaces from most preferred to least preferred for this application as well as the average rating for each interface type.

a small change in the ratings for the Virtual Puck and the Surface Slider interfaces. The interfaces from fastest to slowest as Physical Puck, Surface Slider and finally Virtual Puck. Table 4.53 also contains the average value computed for each interface.

Option	Fastest	Neutral	Slowest	Average
Surface Slider	1	7	4	2.25
Virtual Puck	1	3	8	2.58
Physical Puck	10	2	0	1.17

Table 4.53: Participant responses when asked to rank interfaces from fastest to slowest for this application as well as the average rating for each interface type.

The subjects' ratings above for which they believed was the fastest interface agreed with the results found from the mean in motion time analysis done in Section 4.2.3.2.

CHAPTER 5

DISCUSSION, CONCLUSIONS AND FUTURE WORK

5.1 Discussion

5.1.1 Mapping Application

Although the Mapping Application experiment was not as successful as expected, analysis of the gathered data found significant results that were predicted as well as results that were not anticipated. Four of the data collection methods used for this experiment ended up being troublesome to gather and provided limited to no added value to the experiment. The four metrics that provided little to no added value were the blink rate tracking, skin conductance measurements, heart rate monitoring and the NASA TLX assessment.

Three other metrics gathered during the experiment were gathered without issue but yielded no significant results. When designing the experiment, it was anticipated that the fine motion control for the different interfaces would have different interaction lengths as well as different interaction rates. No significant difference was found between the fine motion control rates and interaction times of the tested interfaces. Also, the transition time between the fine and coarse motion portion of the interfaces was recorded but no difference was expected or found.

The significant results for the Mapping Application experiment were observed between the Surface Slider and both puck interfaces. Users spent significantly more time interacting with the Surface Slider interface overall and users also spent more time interacting with the Surface Slider's coarse motion portion more than the coarse

motion portion of both puck interfaces. We did not expect that the Surface Slider's coarse motion interface would be significantly slower. During the design process, a large effort was devoted to reducing as many differences as possible between the Surface Slider's coarse motion interface and the coarse motion interface for the two puck interfaces. The difference found between the overall motion times of the interfaces seems to be linked directly to the significant difference between mean coarse motion interfaces.

In addition to the data gathered during the experiment, the post-experiment questionnaire had a few important results. To verify that the subjects understood what to do during the experiment, multiple questions were used to check how clear the instructions were and how well they understood the tasks they had to complete. All of the subjects indicated that they thought the instructions were clear and they also agreed that they understood how to complete the tasks. The remaining results for the questionnaire favored the puck interfaces and opposed the surface slider. The Surface Slider was ranked as the least preferred interface for the subjects to use as well as the least fun to use. Also, the subjects indicated that they believed the physical puck was the fastest to use and responded to their actions better when compared to the other two interfaces. Finally, a large majority of the subjects indicated, unexpectedly, that a physical object as a tangible user interface would not make them more likely to use an application.

At multiple points during the analysis it was noticed that many of the results had a p value lower than 0.1 but not lower than 0.05. When starting the experiment, it was expected that more subjects would have participated but a lack of response limited the number of subjects. A longer study with minor changes could yield more significant results but time did not permit for the experiment to be rerun.

5.1.2 Numbers Application

Unlike the first experiment, the Numbers Application was run as a pilot due to limited time and a lack of respondents. The pilot experiment resulted in a collection of findings that suggest that it might be worth running the experiment again under the same conditions or with some minor modifications.

Analysis of the gathered data showed that the Virtual Puck required significantly more time for fine motion traversal but had a significantly higher traversal rate for the the coarse motion interface. The Physical Puck was also significantly faster than the other two interfaces for the mean total task time, in motion time, and the coarse motion time. The fine motion traversal rate was also faster for the Physical Puck than the Surface Slider but no significant difference was found between the Physical Puck and the Virtual Puck. Finally, the eye tracking measurements showed that the Physical Puck interface imparted more cognitive load on the subjects who were using it than the Surface Slider, but the sample set for this data set was very limited.

After the subjects finished their trial they were asked to rank the interfaces based on which the preferred to use and which they thought was the fastest. Analysis of the user responses showed that the Physical Puck interface was preferred over, and considered faster than the other two interfaces. The Surface Slider and the Virtual Puck ended with the same rating for the preference question and the Surface Slider had a marginally higher rating for which interface the subjects thought was the fastest.

The promising results of the pilot experiment suggest that running the numbers application experiment again as a controlled experiment, similar to the mapping application experiment, could find significant results that may contribute to supporting to refuting the hypotheses listed in Section1.3.

5.2 Conclusion

With the data from the Mapping Application experiment, only one of the three hypotheses presented in Section 1.3 could be supported.

Hypothesis 2 predicted that the subjects of the experiments would have a more satisfying experience using the tangible interfaces when compared to the two digital interfaces. The responses of the users in the post-experiment questionnaire of the first experiment found that users felt that the Physical Puck interface was faster and more responsive to their movements. The first experiment found very little difference between the Physical Puck and Virtual Puck interfaces, but there were many results suggesting that more subjects or a longer experiment could provide more significant results.

The second experiment was conducted to try and find more conclusive answers to the other two hypotheses. Due to the limited response from requests for subjects for experiment one, the second experiment was run as a pilot with its subjects drawn from the Project54 staff. The results gathered must be treated as partially biased but could be a suggestion what could result from a more controlled experiment.

Using the results of the second experiment, results of the two remaining hypotheses can be suggested. Hypothesis 1 hypothesized that the users would be faster at extracting data from a dataset with TUIs. The results of the first experiment suggested that Hypothesis 1 might be true and the pilot experiment presented much stronger supporting evidence.

The first experiment was not able to produce any evidence in favor of or in opposition to Hypothesis 3 due to technical difficulties and incomplete data. The pilot experiment had technical difficulties as well, but the small amount of data collected yielded a one significant result suggesting that the Physical Puck interface induced more cognitive load than the Surface Slider interface. The lack of valid data for the

eye tracking, and the possibility of biased participants meant the results from eye tracking could be inaccurate and should be investigated further.

Overall, both experiments resulted in positive results and data in favor of further work towards development of tangible user interfaces for touch screen interactions for mapping applications.

5.3 Future Work

Both experiments conducted had promising results for the investigation of tangible user interfaces for mapping applications. There are a few possible areas for improvement and future work in the mapping applications with tangible user interfaces field that are been listed below.

1. As some of the subjects from the first experiment suggested, the Physical Puck interface could be cut in half or redesigned to make the scrubber more visible to a user sitting in front of the table. More information about the suggestions can be found in Section 4.1.6.6.
2. Like the first example, the subjects of the first experiment suggested that the Virtual Puck interface should be altered to prevent the interface from jumping through points quickly when the center point is crossed or when their finger leaves the circle. The suggestions for the Virtual Puck interface were discussed in Section 4.1.6.6.
3. Estimating relative cognitive load for the interfaces proved to be a difficult task for these experiments. If more reliable methods can be found or new implementations of existing methods are available, rerunning both of these experiments could yield new or better results.

4. The easiest way to get another set of results would be to try both of these experiments again with a larger sample size as well as non connected subjects (in the case of the second experiment).
5. Explore the design of the coarse motion interface designs to try and learn why the new scrubber was so much faster, in both time and traversal rate than the control. One possible avenue could involve investigating the kinematics of a linear scrubber when compared to a semi-circular scrubber.

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Appendices

APPENDIX A
CONSENT FORM

INSTITUTIONAL REVIEW BOARD FOR THE PROTECTION OF HUMAN SUBJECTS IN RESEARCH

Purpose: This research is funded by the National Institute of Justice (NIJ). The purpose of this research is to assist in the development of user interfaces for vehicles, handheld computers and multi-touch surfaces. Another goal is to develop specific applications for vehicles, handheld computers, and multi-touch surfaces.

Procedure:

- ☐ You will be asked to interact with the Project54 system running on a PC and/or on a handheld computer. You may also be asked to perform a physical task, such as operating a driving simulator. The Project54 system will record your speech, and/or your interactions with the GUI and/or your interactions with original hardware interfaces, and/or data generated by electronic devices that you interact with and/or data generated by electronic devices that the Project54 system interacts with. The recording will require no special steps on your part. You will also be asked to respond to questionnaires that will ask for personal information and feedback about the experiment.
- ☐ You will be asked to interact with a PC, and/or on a handheld computer, and/or a multi-touch surface, and/or other electronic devices and physical objects. You may also be asked to perform a physical task, such as operating a driving simulator, or walking and taking pictures with the handheld computer, or manipulating physical objects that control a multi-touch surface. We will take photographs, and/or create audio and/or video recordings of your interactions. We will also record your interactions with the computer's user interface and/or your interactions with other hardware interfaces, and/or data generated by the computer and/or by the electronic devices. We may also record physiological measurements from sensors attached to your body (e.g. temperature, electrocardiogram, skin conductance sensors), and/or sensors in your environment (e.g. pressure sensors on objects in your environment, gaze and head position trackers). You will also be asked to respond to questionnaires that will ask for personal information and feedback about the experiment.

Data generated in this research will be saved for use in future research. A unique ID will be assigned to you. The unique ID will be of the form "User #xx", where xx is the number assigned to you. It will be used to label your data, along with your age, gender, characteristics of your physical interactions with various devices, your experience in working with computers or the Project54 system and any questionnaires you fill out. The data will be stored for future use in our research; there is no set date for destruction of the data, and it may be kept for an unlimited duration. Your identity will not be tied to the data in any way other than to the video data, if such data is created, since video data may visually identify you. Video data may be generated by stand-alone video cameras and by cameras that are part of a gaze and head tracker. In this document we are asking for your consent to participate in our study and to share the non-video data with researchers from other institutions. Separately we ask for your consent to share video data with researchers from other institutions, to include still shots from videos in scientific publications and technical reports, as well as to show video data at conferences and similar meetings. Finally, we also ask for your consent to share video data with the public by posting video clips, or still shots from the clips, online (on sites such as Flickr or YouTube), or by including them in printed publications.

The only risks associated with this research are the potential of skin irritation from sensors attached to your body and the potential for motion sickness if operating a driving simulator. There should be no aftereffects of this research upon you. You will be compensated at approximately \$____/hour for your effort. Your compensation may be in the form of a check or in the form of a gift certificate or in the form of a software license (provided by Microsoft). You may have to fill out a W-9 form. Checks will be mailed by UNH. Your compensation may be reported to the IRS.

1. You understand that the use of human subjects in this project has been approved by the UNH Institutional Review Board for the Protection of Human Subjects in Research.

2. You understand the scope, aims, and purposes of this research project and the procedures to be followed and the expected duration of your participation.
3. You have received a description of any reasonable foreseeable risks or discomforts associated with being a subject in this research, have had them explained to you, and understand them.
4. You have received a description of any potential benefits that may be accrued from this research and understand how they may affect you or others.
5. The investigator seeks to maintain the confidentiality of all data and records associated with your participation in this research. You should understand, however, there are rare instances when in order to comply with policy, regulations or laws, the investigator is required to share personally-identifiable information for research related purposes. (e.g., officials at the University of New Hampshire, designees of the sponsor(s), and/or regulatory and oversight government agencies may require access to research data in order to investigate a complaint about the conduct of the research). Personally-identifiable information will not be released for non-research purposes without your prior consent.
6. You understand that your consent to participate in this research is entirely voluntary, and that your refusal to participate will involve no prejudice, penalty or loss of benefits to which you would otherwise be entitled.
7. You further understand that if you consent to participate, you may discontinue your participation at any time without prejudice, penalty, or loss of benefits to which you would otherwise be entitled.
8. You confirm that no coercion of any kind was used in seeking your participation in this research project.
9. You understand that if you have any questions pertaining to the research you can call Dr. Andrew Kun at 603-862-4175 and be given the opportunity to discuss them. If you have questions pertaining to your rights as a research subject you can call Julie Simpson in the UNH Research Integrity Services, 603-862-2003, to discuss them.
10. You understand that your age, gender, the characteristics of your speech, and your experience in working with computers or the Project54 system will be recorded, and may be shared with other researchers, along with the data collected about your interactions.
11. You certify that you have read and fully understand the purpose of this research project and the risks and benefits it presents to you as stated above.

I, _____ CONSENT/AGREE to participate in this research project.

I, _____ REFUSE/DO NOT AGREE to participate in this research project.

Signature of Subject

Date

I, _____ CONSENT/AGREE to allow sharing photographic and video data with other researchers, including still shots from videos, in scientific publications and technical reports, and showing video data at conferences and similar meetings.

I, _____ REFUSE/DO NOT AGREE to allow sharing photographic and video data with other researchers or showing it at conferences and similar meetings.

Signature of Subject

Date

I, _____ CONSENT/AGREE to allow sharing photographic and video data with the public by posting pictures, video clips, or still shots from the clips, online, or by including them in printed publications.

I, _____

REFUSE/DO NOT AGREE to allow sharing photographic and video data with the public by posting pictures, video clips, or still shots from the clips, online, or by including them in printed publications.

Signature of Subject

Date

APPENDIX B

PERSONAL INFORMATION QUESTIONNAIRE

Personal Information Questionnaire

Subject ID: _____ Date: _____ Time: _____

About you

1. How old are you? I am _____ years old.
2. What is your gender? ☐ Male ☐ Female
3. Are you a student? ☐ Yes ☐ No
4. If you are a student, what is your standing?
 - ☐ Freshman
 - ☐ Sophomore
 - ☐ Junior
 - ☐ Senior
 - ☐ Graduate
5. If you are not student, what is your highest education level?
 - ☐ High School
 - ☐ College
 - ☐ Graduate
6. Have you ever used a iPod device with a scroll wheel (circular selector)?
 - ☐ Yes ☐ No
7. Which is your dominant hand?
 - ☐ Right ☐ Left ☐ Neither

Experience with touch screen technology

For the following questions, a touch screen interface is a method of interacting with a device using your finger(s) to touch the graphic display of the device. Examples of this include touch screen phones, touch based tablets, touch tables and store kiosks. If you are unsure if a specific device has a touch screen interface, please ask the experimenter.

8. Do you have experience with touch screen interfaces?
 - ☐ Yes ☐ No
9. Do you use a device with a touch screen interface on a regular basis?
 - ☐ Yes ☐ No
10. If yes, how often do you use the touch capabilities of each of the following devices? Please mark the correct column with an X for each row.

Device	More than once a day	Once a Day	A few times a week	Once a week	Less than once a week	I do not use touch on this device
Desktop Computer						
Laptop Computer						
Cell Phone / PDA						
Tablet						
Other (List Below)						

11. If other, what _____

Experience with mapping software

For the following questions, mapping software are programs that allow their users to explore mapping information or geocoded data. Examples of these programs include Google Earth, Google Maps, Bing Maps, GIS. If you are unsure if a specific application is considered mapping software, please ask the experimenter.

12. Do you have any experience with mapping software?

☐ Yes ☐ No

13. Do you use mapping software on a regular basis?

☐ Yes ☐ No

14. If yes, how often do you use mapping software? Please mark the correct column with an X for each row.

Software	More than once a day	Once a Day	A few times a week	Once a week	Less than once a week	I do not use this mapping software
Google Maps						
Google Earth						
Bing Maps						
Virtual Earth						
GIS						
Other (List Below)						

15. If other, what _____

16. Have you used any mapping software with touch screen technology?

☐ Yes ☐ No

17. If Yes, how often do you use mapping software with touch screen technology on the devices below?

Device	More than once a day	Once a Day	A few times a week	Once a week	Less than once a week	I do not use touch with mapping software on this device
Desktop Computer						
Laptop Computer						
Cell Phone / PDA						
Tablet						
Other (List Below)						

18. If other, what _____

Experience with tangible user interfaces

For the following questions, a tangible user interface is a tangible device for interacting with a computer other than a keyboard, mouse or a stylus. Examples of this include video editing pucks or a Nintendo Wii game controller.

19. Do you have any experience with tangible user interfaces?

☐ Yes ☐ No

20. Do you own, or use on a regular basis, a device with a tangible user interface?

☐ Yes ☐ No

21. If yes, how often do you use a tangible user interface (TUI)? Please mark the correct column with an X for each row.

TUI	More than once a day	Once a Day	A few times a week	Once a week	Less than once a week	I do not use touch on this device
Nintendo Wii Con- troller						
Video Editing Puck						
Other (List Below)						

22. If other, what _____

APPENDIX C
NASA-TLX DEFINITION SHEET [1]

Appendix A

RATING SCALE DEFINITIONS		
Title	Endpoints	Descriptions
MENTAL DEMAND	<i>Low/High</i>	How much mental and perceptual activity was required (e.g., thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?
PHYSICAL DEMAND	<i>Low/High</i>	How much physical activity was required (e.g., pushing, pulling, turning, controlling, activating, etc.)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?
TEMPORAL DEMAND	<i>Low/High</i>	How much time pressure did you feel due to the rate or pace at which the tasks or task elements occurred? Was the pace slow and leisurely or rapid and frantic?
EFFORT	<i>Low/High</i>	How hard did you have to work (mentally and physically) to accomplish your level of performance?
PERFORMANCE	<i>Good/Poor</i>	How successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals?
FRUSTRATION LEVEL	<i>Low/High</i>	How insecure, discouraged, irritated, stressed and annoyed versus secure, gratified, content, relaxed and complacent did you feel during the task?

APPENDIX D
EXPERIMENT QUESTIONNAIRE

Experiment Questionnaire

Subject ID: _____ Date: _____ Time: _____

Experiment

Please indicate the level of agreement with each of the statements below by circling one of the five possible answers.

1. The instructions at the beginning of the experiment were clear.

Strongly Disagree Disagree Neither agree nor disagree Agree Strongly Agree

2. The instructions at the beginning of the Surface Slider portion were clear.

Strongly Disagree Disagree Neither agree nor disagree Agree Strongly Agree

3. The instructions at the beginning of the Virtual Puck portion were clear.

Strongly Disagree Disagree Neither agree nor disagree Agree Strongly Agree

4. The instructions at the beginning of the Physical Puck portion were clear.

Strongly Disagree Disagree Neither agree nor disagree Agree Strongly Agree

Overview

5. Please rank each of the interfaces based on which you would prefer to use with 1 being the highest preference and 3 being the lowest.

_____ Surface Slider

_____ Virtual Puck

_____ Physical Puck

6. Please rank each of the interfaces based on how fast you were able to find the data of interest with 1 being the fastest interface and 3 being the slowest.

_____ Surface Slider

_____ Virtual Puck

_____ Physical Puck

Please indicate the level of agreement with the statement below by circling one of the five possible answers.

7. I would be more likely to use an application if it had tangible (physical) objects to interact with, such as the puck.

Strongly Disagree Disagree Neither agree nor disagree Agree Strongly Agree

Surface Slider

Please indicate the level of agreement with each of the statements below by circling one of the five possible answers relating only to the tasks involving the **Surface Slider** interface.

8. I understood how to find the answer for each question.

Strongly Disagree Disagree Neither agree nor disagree Agree Strongly Agree

9. The interface responded to my movements as I anticipated.

Strongly Disagree Disagree Neither agree nor disagree Agree Strongly Agree

10. The interface was easy to use.

Strongly Disagree Disagree Neither agree nor disagree Agree Strongly Agree

11. The interface was fun to use.

Strongly Disagree Disagree Neither agree nor disagree Agree Strongly Agree

Virtual Puck

Please indicate the level of agreement with each of the statements below by circling one of the five possible answers relating only to the tasks involving the **Virtual Puck** interface.

12. I understood how to find the answer for each question.

Strongly Disagree Disagree Neither agree nor disagree Agree Strongly Agree

13. The interface responded to my movements as I anticipated.

Strongly Disagree Disagree Neither agree nor disagree Agree Strongly Agree

14. The interface was easy to use.

Strongly Disagree Disagree Neither agree nor disagree Agree Strongly Agree

15. The interface was fun to use.

Strongly Disagree Disagree Neither agree nor disagree Agree Strongly Agree

Physical Puck

Please indicate the level of agreement with each of the statements below by circling one of the five possible answers relating only to the tasks involving the **Physical Puck** interface.

16. I understood how to find the answer for each question.

Strongly Disagree Disagree Neither agree nor disagree Agree Strongly Agree

17. The interface responded to my movements as I anticipated.

Strongly Disagree Disagree Neither agree nor disagree Agree Strongly Agree

18. The interface was easy to use.

Strongly Disagree Disagree Neither agree nor disagree Agree Strongly Agree

19. The interface was fun to use.

Strongly Disagree Disagree Neither agree nor disagree Agree Strongly Agree

Other**20. Comments, suggestions or other feedback:**

APPENDIX E
IRB APPROVAL

University of New Hampshire

Research Integrity Services, Service Building
51 College Road, Durham, NH 03824-3585
Fax: 603-862-3564

16-Jul-2012

Kun, Andrew L
Electrical & Computer Eng Dept
Kingsbury Hall
Durham, NH 03824

IRB #: 2980

Study: Speech Sample Collection for Speech Recognition Engine Comparison and Development

Review Level: Expedited

Approval Expiration Date: 24-Jun-2013

The Institutional Review Board for the Protection of Human Subjects in Research (IRB) has reviewed and approved your request for time extension for this study. Approval for this study expires on the date indicated above. At the end of the approval period you will be asked to submit a report with regard to the involvement of human subjects. If your study is still active, you may apply for extension of IRB approval through this office.

Researchers who conduct studies involving human subjects have responsibilities as outlined in the document, *Responsibilities of Directors of Research Studies Involving Human Subjects*. This document is available at <http://unh.edu/research/irb-application-resources> or from me.

If you have questions or concerns about your study or this approval, please feel free to contact me at 603-862-2003 or Julie.simpson@unh.edu. Please refer to the IRB # above in all correspondence related to this study. The IRB wishes you success with your research.

For the IRB,



Julie F. Simpson
Director

cc: File