IMPROVING BIMANUAL HUMAN-COMPUTER INTERACTION USING FORCE DISPLAY

by

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ABSTRACT

In computing, haptics is the science of applying tactile sensation and force feedback to human interaction with computers. The effect of haptics on human performance in a bimanual task was investigated. Twelve participants performed an asymmetric bimanual two dimensional drawing task in three conditions: with no computer generated force feedback, with force enabled in the left hand only, and with force enabled in the right hand only. Participants showed no significant improvement in performance with force feedback present on either hand compared to no force feedback. Subjectively, most participants preferred the presence of force. This implies that force, though not significantly effective in such tasks, affords satisfaction for the user.

DEDICATION

Dedicated to my family, my constant source of love & support:

Parents: Charles & Patricia Knight

Sister: Susan.

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I acknowledge with gratitude the big debts that I owe to many friends and colleagues who contributed to this project. First and foremost, I am sincerely grateful and forever indebted to Nabye H.S. Wilson for his never-ending support, both morally and physically. His comfort and understanding were instrumental to the completion of this work. Without him I would have been devoid of a fantastic companion and most definitely would have starved to death or at least collapsed from exhaustion!

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1: INTRODUCTION

Despite being a bimanual species, humans are generally limited to unimanual communication when interacting with computers. This unimanual approach involves the use of the dominant hand for everything from painting to navigating a menu. Most human activities are two-handed, but most human-computer interaction (HCI) techniques employ only one hand. As such, these techniques do not exploit bimanual skills from lifelong learning. These systems poorly engage the hands and do not reflect the natural asymmetric movement of users. Though the mouse is one of the most precise pointing devices in computing, the human hands and fingers have the dexterity to express many levels of symmetric and asymmetric interactions. Some of this dexterity is exploited by the keyboard and video game controllers, the most common exceptions to unimanual computing. Though the keyboard and mouse are frequently used bimanually, they accomplish two very different tasks and rarely rely on inter-manual coordination. There is the need for a conscious switch to a different technique, a phenomena rarely present in our well-practiced everyday tasks. Our everyday skills are so well ingrained that little cognitive effort is required for task completion. HCI could greatly benefit from exploiting our two-handed nature and involving bimanual interaction in computing.

While many researchers have investigated the use of two-handed computing, few have considered the edge force feedback could give in human performance. Force feedback is present in a wide variety of non-computer bimanual tasks. Driving a manual transmission automobile is one such task. The driver is required to have one hand on the wheel and the other on the gearshift. In manipulating the gearshift, the driver needs only to feel the movement between gears, greatly alleviating visual load. Visual confirmation is rarely required and, in fact, is quite impractical and hazardous, as one's eyes should be focused on the road. Another example is manipulating the lid on a jar. Haptic feedback is a major component in coordinating the two hands. We can feel the lid loosen or tighten and visual confirmation is unnecessary. In fact, attempting to determine the state of a lid on a jar visually is insufficient. The force feedback tells us what we need to know and, consequently, what we need to do (or not do). However, this cue of force feedback, omnipresent in bimanual interaction with physical objects, is absent in two-handed computer interaction techniques.

Observing the physical world, we can see that bimanual interaction is common in tasks when there is the dependence on one subtask on another, such as the jar example given above. The hands are assigned domain specific tasks, with the non- dominant hand performing broad, coarse actions such as holding or stabilizing the jar and the dominant hand performing precise actions such as manipulating the lid.

Yves Guiard proposed a theory that models the performance of such asymmetric bimanual action as a chain of abstract motors (Guiard, 1987). Known as the Kinematic Chain Model, this theory involves a principle that describes this subtask dependence as divisions of labour between the two hands.

Building on these ideas of two-handed, asymmetric interaction and force feedback, this project used a haptic "pull" effect to coordinate hands in a bimanual task. A user study in which users interacted with a graphical environment using a common bimanual interaction technique was conducted to determine the effects of haptic feedback on users performing tasks based on Guiard's theory. The results were disappointing, showing no significant impact on user performance. However, users showed a strong preference for force feedback. This indicates some potential benefits of incorporating force into bimanual interactions for a more natural relation. These benefits can lead human computer interactions to become akin to the two-handed, force driven methods employed in everyday life.

Section 2 will present a background and discussion of the issues in bimanual computing, a concise look at Guiard's theory, and a brief description of the interaction techniques implemented. Section 3 discusses the design of a controlled user study and section 4 discusses the results. Section 5 serves as a discussion and conclusion, leading to ideas for future work.

2: RESEARCH QUESTIONS

2.1 Introduction

This chapter serves to introduce and discuss the previous work conducted in the fields of bimanual, haptic, and bimanual haptic interactions. Due to the two-handed nature of humans, bimanual interaction holds great potential in human-computer interaction. However, with the advent of computers came the use of conventional uni-manual input devices such as the mouse, designed to allow the user to "point and click" on a display screen. With the exception of the keyboard and video game controllers, nothing in terms of two-handed computing has become mainstream. Researchers have shown that incorporating bimanual interaction into traditional computing can yield faster task completion times (Dennerlein, Martin, & Hasser 2000; Balakrishnan & Hinckley 1999).

The ubiquitous force feedback in keyboards and, more recently, vibrations in video game controllers have also proven advantageous. However, the forces in these devices differ from those presented in this project as well as from each other. The feedback in keyboards is more kinesthetic. Requiring minimum adequate force, keyboard keys provide distinct contact feedback to the user when the keys are maximally depressed. This feedback does not vary to indicate current program states, a possibility that seems unique to haptic displays. In contrast, the vibratory cues in video game controllers enhance the sense of user immersion and modes of interaction. The controllers often shake when certain activities occur, such as a player's character getting hit or running into a wall.

The force described in this project is neither vibratory nor kinesthetic and does not act solely because of the user's action. Rather, in addition to notifying the users of their action, it is a guidance cue to help users proceed correctly. In keyboards and controllers, this type of verification is presented visually, with force simply enhancing the experience. Additionally, the force feedback as a guiding factor serves to accelerate hand movement.

Force feedback is natural in the physical world and essential in computing devices such as the keyboard and controller. Furthermore, research has shown that force feedback yields benefits in unimanual computing. Combining these ideas, we can thus explore the question: *Can the perception of force between the hands improve bimanual interaction in a virtual environment*?

To explore this idea, a bimanual interaction technique theoretically based on Guiard's Kinematic Chain Model (KC) was implemented in an experimental study. The KC model recognizes that, in asymmetric movement, the two hands are engaged in different tasks. It is quite clear that two hands carry out distinct jobs in activities such as playing an instrument or unscrewing a jar. The KC model is an observation of how these jobs are executed. A brief background into the model and its working principles is given. The present study made use of the common bimanual interaction technique Toolglass (Bier, Stone, Pier, Buxton, & DeRose, 1993). The Toolglass will be described in section 2.3.

2.2 Guiard's Kinematic Chain Model

In asymmetric bimanual interaction, the hands are assigned different roles, as is the case in everyday activities such as sweeping, hand writing, or unscrewing the lid of a jar. Essential in developing much of the current design and experimental research in bimanual interaction, Guiard's kinematic chain model is a general theory of skilled bimanual action that describes this division of labour. Two fundamental constituents comprise the model. The first says that the two hands are akin to a pair of abstract motors. Guiard defined a motor as any device, natural or artificial, whose purpose is to generate motion. The word "abstract" refers to the fact that no attempt will be made to rationalize the internal mechanisms that engage the motor. The second constituent of the model says that these two motors are apt to be serially assembled, thereby forming a functional *kinematic chain* (Guiard, 1987). For example, the chain can be representative of the human arm. The chain is composed of the arm, forearm, wrist, and fingers, elements that have distinct features and functions.

For each link in the kinematic chain, there is a proximal (dominant) and distal (non-dominant) element. Using the forearm as a link in our arm chain, the distal element equates to the wrist and the proximal element to the elbow. The model states that the proximal dominant element articulates its motion relative to the frame of reference set by the distal non-dominant element. In our example, this means the hand moves according to the relative output of the elbow due to their physical attachment. The Kinematic Chain models the left and right hands as a functional kinematic chain, with the dominant hand the distal element and the non-dominant hand the proximal element. For right-handers, the left hand 'leads' and the right hand 'follows' (Guiard, 1987).

The serial assemblage of the two abstract motors requires them to act on a common aspect of motion, with the output from one motor serving as the input to the other. A serial assemblage has the property of partial dependence. The motion of one motor depends on the motion of the other, while the inverse is false. The asymmetric division of labour in a serial assemblage makes it an appropriate model for the way the human hands often collaborate with each other. For example, in writing with a pen on a desk, the dominant hand moves the pen with reference to the page. The non-dominant hand manipulates the page relative to the desk (Guiard, 1987).

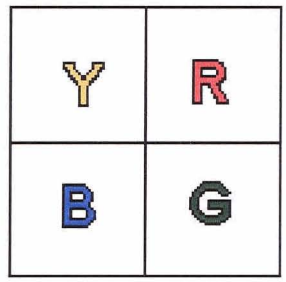
Guiard has proposed three high order principles that describe the functional relationship between hands in standard asymmetric human motion. The kinematic chain model accounts for these three principles. Guiard shows the existence of a strong functional correlation between the cooperative habits of the two motors and these three principles. The first principle, *Distal-to-proximal spatial reference*, states that the non-dominant hand sets the frame of reference for the motion of the dominant hand. The motors, being the hands, do not operate independently and in parallel. Rather, they function together to accomplish their tasks. The marked specialization of the hands specifies a chain of reference frames. This principle will be referred to as "Guiard's reference principle" for the remainder of this document. The second principle, *Proximal-distal contrast in the spatial-temporal scale of motion*, says that the hands operate asymmetrically over space and time. The movements of the dominant hand are more frequent and precise than those of the non-preferred hand. For example, the writing movements of the dominant hand are more frequent and exact than the paper-positioning movements of the non-dominant hand. The third principle asserts that the non-dominant precedes the dominant hand in performing co-operative tasks. This principle is referred to as *Proximal precedence* (Guiard, 1987).

To implement a bimanual task as suggested by the Guiard reference principle, two cursors are needed, one of which must perform the coarse actions of the non-dominant hand and the other the precise actions of the dominant hand. This implementation is often achieved with a Toolglass widget.

2.3 Toolglass - A Bimanual Interaction Technique

Based on Guiard's model, the Toolglass interaction technique was implemented in this project. The Toolglass widget is a semi-transparent interactive user interface tool that appears between an application and a traditional cursor. Positioned with one hand, while the other hand positions a traditional arrow cursor, the Toolglass has been used for bimanual interaction techniques in research systems such as CPN2000 (Beaudouin-Lafon & Lassen, 2000) and T3 (Kurtenbach, Fitzmaurice, Baudel, & Buxton, 1997). The widgets can feature visual filters that alter the presentation of application objects, revealing hidden information, augmenting areas of interest, or suppressing distracting data. Appearing on a virtual sheet of transparent "glass", the widget provides an interactive view of the application underneath. Two hands can be used to operate this *see-through* interface as the user can simultaneously coarsely position the sheet with the non-dominant hand, while the dominant hand precisely positions a cursor. The user can line up a cursor, a widget, and an application object in a single two-handed gesture (Bier et. al., 1993). In this project, the Toolglass, as depicted in Figure 2.1, was used only for its combined command selection and location selection ability. Users moved the widget to a location and selected one of four coloured letters. The Toolglass widget provided a set of constraints and possibilities for the actions of the distal element of the kinematic chain.

Figure 2.1: Toolglass widget divided into four quadrants with coloured letters Y, R, B, G. The four letters are coloured to respectively represent Yellow, Red, Blue, and Green. Users click in a quadrant to select a colour.



Kabbash, Buxton, and Sellen (1994) compared the use of four interaction techniques in an experiment in which subjects drew coloured line segments between a set of twelve dots displayed on a monitor. Three of these four techniques were bimanual, including the Toolglass. Subjects achieved faster performance using the Toolglass (mean 2.43 s), on average executing the task 0.46 seconds faster than with the next best technique and 0.53 seconds faster than the slowest. Nine out of ten subjects preferred using the Toolglass technique.

2.4 Related Experimental Studies

Buxton and Myers (1986) showed that computer users naturally use two hands to perform compound tasks, resulting in improved task performance. Since then, much research on bimanual interaction has been done, most involving the kinematic chain model as a theoretical basis. While Guiard states his reference principle generally, Balakrishnan and Hinckley (1999) proceeded to determine whether it would hold true for disjointed combinations of kinesthetic and visual feedback. They presented an experiment exploring the influence on two-handed input that the difference between the input space of the hands and the output space of a graphical display makes. The study yielded important implications for bimanual interaction design and for Guiard's reference principle. As long as appropriate visual feedback was present, both bimanual input performance and the Guiard reference principle were resilient when both hands operated in the same physical space (unified), when each hand operated in a separate physical space (separated), and when each hand operated in its own separate space whose origin changed each time the device was clutched (relative). There was no effect between the physical separations of hands and the position of the hands as sensed by input devices. Guiard's reference principle was resilient in a direct association between the two (Balakrishnan & Hinckley, 1999).

Jason Sze (2003) incorporated the above findings of visual feedback in separated reference frames and Guiard's reference principle into an experiment to test theoretical predictions of various forms of feedback for non-dominant hand location in the graphical user interface environment. Using the Toolglass for interaction, Sze (2003) assessed four forms of system feedback: no feedback of Toolglass position, graphical display only, force feedback only, and the combination of graphical and force feedback. He hypothesized that the combined feedback would yield better performance than graphics alone and that force feedback would elicit at least as good performance as graphics alone. Combining force with graphical feedback yielded an 8% improvement in user task completion time over graphical and force feedback individually. Graphical and force feedback yielded similar results to each other, each approximately 38% better than no system feedback.

Further consideration of Sze's interaction technique revealed a contradiction of Guiard's reference principle. Sze's technique required the user to move their dominant hand first to the target object. This meant that the non-dominant hand was moving in response to the frame of reference set by the dominant hand (Sze, 2003). This contradiction leaves Sze's results, though certainly promising, with some question as to the applicable range of tasks. Tasks performed in such a way are not representative of the way users accomplish actual tasks. We surmise that a more natural human interaction technique, one better adhering to the reference principle, would yield better performance.

A formal knowledge of bimanual interactions is incomplete without that of how the two hands cooperate to achieve a common objective. Investigating this phenomena, Hinckley, Pausch, Proffitt, Patten, and Kassel (1997) discussed a "Cooperative Bimanual Action" study of a three dimensional user interface based on bimanual physical manipulation of hand held implements. An experimental task required right-handed individuals to manipulate a pair of physical objects: a tool and target/reference object. Participants were required to use the tool to touch the target, combining the hands' actions to achieve a common goal. Generally, performance was best when the left (non-dominant) hand oriented the target object and the right (dominant) hand manipulated the tool, a result siding with other studies and discussions that supported Guiard's reference principle (Guiard 1987; Guiard & Ferrand 1996; Kabbash et. al. 1994). Combining the experimental evidence which favoured their hypotheses, there was an indication that, due to the necessary change in motor control type, haptic feedback greatly simplified the task for both hands. This suggests that active feedback from haptic devices can have a crucial bearing on some tasks. The task can be routinely executed allowing the user to devote full visual attention to a high-level task instead of a low-level tool acquisition sub-task (Hinckley et. al, 1997).

Whilst haptic feedback has been shown to improve user performance in target tasks in such studies as discussed previously, Oakley, Adams, Brewster, and Gray (2002) argued that the single target nature of some studies' tasks may not generalize well to more realistic, multi-target interfaces. In two empirical studies dealing with groups of haptically enhanced widgets, Oakley et. al. (2002) showed that haptic augmentations of complex widgets actually reduced performance. An experimental study of haptically enhanced menus by Oakley, Brewster, and Gray (2001) showed that moderating the haptic effects according to the speed of the user's movements to a menu item can dampen the reduced performance. The haptically augmented menu was designed to support a user's typical menu interaction, reducing force along each individual axis proportionally to the user's speed along the opposite axis. This resulted in weak forces opposing a user's motion or strong forces supporting it instead of a tunnel-like force where the menu items were simply lined with haptic walls. Though a 48% reduction in error rates was found, there was no significant difference in speed. This result coincided with those of another study conducted by Oakley, McGee, Brewster, and Gray (2000). Haptically augmenting scrollbars and buttons resulted in no performance improvement but significantly reduced error rates. This study was limited in that it required knowledge of where the user is moving to on the interface. Typically, this knowledge is unavailable. However, in bimanual computing, we have a clue to the user's movement based on the reference principle. While we do not know where the non-dominant hand is going, we can guess where the dominant hand is going because it is following the non-dominant hand.

Also concerned with design considerations in haptic environments, Bernstein, Lawrence, and Pao (2003) focused on incorporating non-dominant hand interactions in haptic interfaces. They developed a bimanual interaction technique featuring haptic feedback to the non-dominant hand in a one-handed haptic interface. Object-object interaction and haptic snap-to-grid effects were applied to a 3D object editor, but no results for these effects were reported.

A unimanual interaction study by Dennerlein et. al. (2000) further suggests benefits of haptic feedback by showing improved performance times with force constraints. The study showed that force feedback improved user performance in steering and steering-targeted tasks. In their experiment, a force field, designed to provide a type of 'groove' for the user to move the cursor in, pulled the mouse cursor to the centre of the steering tunnel. This experiment yielded a 52% faster completion time with the force feedback mouse compared to the conventional mouse (Dennerlein et. al, 2000). The research by Dennerlein et. al. dealt with only one potential target in pointing and steering tasks, leaving open the question of whether force feedback benefits bimanual interactions in more realistic, multi-targeted interfaces.

2.5 Hypotheses

The above results show a naturalness and effectiveness of bimanual interaction to users performing techniques based on Guiard's reference principle as well as the benefits of force feedback. Buxton and Myers (1986) showed that computer users naturally use two hands to perform compound tasks, resulting in improved task performance. Balakrishnan and Hinckley (1999) have shown visual feedback to be essential for efficient bimanual performance when conventional pointing devices employ both hands in two separate kinesthetic frames. As in the real world, natural force and tactile feedback are helpful to both uni- and bimanual interactions. While Dennerlein et. al. (2000) achieved improvement with force in unimanual interactions, their work did not account for more realistic, multi-targeted interfaces as is the case in this project. Their study was based on steering tasks rather than the pointing tasks used in Sze's work, the precursor to this project. Although Sze demonstrated that force improves bimanual interaction, his results seemed better fitted for a different, less common range of user tasks.

This contradiction leaves open the possibility that, with a task more representative of how people work with actual interfaces, a larger difference in performance might be found. It is possible that with this seemingly more natural way of interacting, users may be given more cues to decrease their visual and, perhaps even their cognitive load. They need not rely on vision to guide hand movement and are thus able to better concentrate on the preciseness of tasks. The first question explored in this project is, *What effects does force feedback have on task completion time and accuracy for users performing asymmetric bimanual tasks, with each hand assigned a unique job?* Furthermore, the contradiction of the reference principle gives credibility in the sense that force still improved performance, regardless of the relative motion of the hands. This leads to another question explored: *If force does improve bimanual interaction, does it function* *so effectively that it can cause users to naturally and comfortably break the habit observed in Guiard's reference principle and switch hand movements to accomplish a task?* If this is the case, force is of large value in asymmetric bimanual HCI. Users will be able to comfortably use either hand provided the necessary feedback is present.

The first hypothesis investigated in this project is that force will indeed have a bigger impact on user completion time in a combined command and location selection input task in which both hands move to a similar location. The works cited in this section have shown that force fields and haptically augmented controls, though crucially limited, are successful in WIMP interfaces. However, little has been done in the field of bimanual interactions. Given Guiard's contribution, one can surmise the movements of inter-manual coordination, with the dominant hand following the non-dominant hand. The force applied in the present study and further discussed in section 3 ultimately results in the hands being brought together faster. Applying force to the dominant hand is expected to accelerate said hand to its known position within the reference frame of the non-dominant hand, improving performance. An increase in performance may also be possible by reversing the habit of non-dominant leading dominant by accelerating the latter into the former's reference frame. This would result in the non-dominant hand being pulled to the location of the dominant hand.

Accuracy should remain relatively the same in all conditions. With the force feedback, the differing factor is the rate at which the user's hands are drawn together. Once in the correct position, users should have no problem completing their task, regardless of how fast their hands are positioned.

3: EXPERIMENTAL DESIGN

3.1 Introduction

I conducted an experiment to test the effect that force feedback has on task completion time (TCT) and accuracy and to determine what effects, if any, are present if the Guiard reference principle is challenged. As part of the experiment, I designed a task more representative of actual interface use with the Guiard reference principle in mind. The task featured two graphical cursors, controlled by haptic devices, with a Toolglass widget and a black arrow cursor. This chapter primarily serves as a discussion and analysis of the experimental design.

The aim of the experiment was, in part, to note a significant difference in performance if haptic feedback was present in a bimanual selection task. As such, I implemented an interaction technique that would be more effective if users moved as predicted by Guiard's reference principle. Additionally, I implemented a technique in which movement by contradicting the principle would be more effective. This allowed for determining if force feedback would cause users to break habit and effectively work in an unfamiliar way.

I modified Dillon, Edey, and Tombaugh's (1990) task to create a style of hand movement that conformed to Guiard's principles. The modified task also more realistically represented typical computer use where there is generally no correlation between a task previously accomplished and a new task to be executed. Users regularly have to move to a new location to accomplish a new task. Rarely is it the case that the final position of a previous task is the starting point of a new task.

Previous attempts at answering questions similar to those posed in the previous section involved the use of the Toolglass interaction technique in experimental studies. As such, this experiment included an implementation of the Toolglass. Additionally, its success in the field of bimanual interaction made the Toolglass an appropriate choice.

Previous works using the Toolglass implemented the colour menu with pure colour swatches (Guimbretiere, Martin, & Winograd 2005; Bier, Stone, Pier, Buxton, & DeRose 1993). The Toolglass for this project used coloured letters swatches. Based of the Stroop effect, I believed that having the first letter of the word be shaded in the colour the word represents would help users match colours. The letter denoting the colour and the actual shade of the letter reinforced the colour representation.

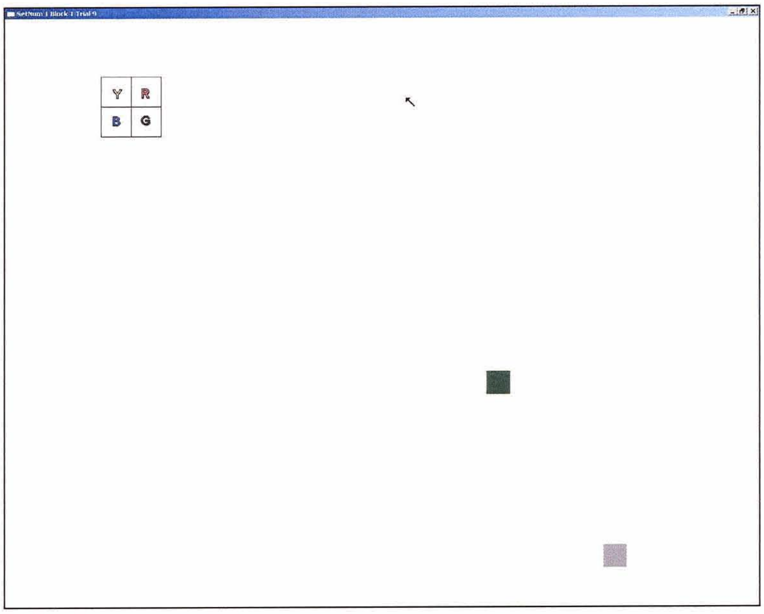
The experiment featured a within-subject design with a single factor, interaction technique, consisting of three levels: no force feedback, force feedback in the left hand, and force feedback in the right hand. User performance was measured by task completion time and accuracy of colour selection. Workload was measured by way of NASA-TLX. Additionally, subjective comments from users were collected.

3.2 Task

Based on the command selection and execution task proposed by Dillon et. al. (1990) and exploited in works such as those by Balakrishnan and Hinckley (1999) and Kabbash et. al (1994), the task implemented in the experimental software consisted of two subtasks. The first subtask was the act of moving both hands to a starting location and selecting a colour. The principles of interest in this project were tested in the first subtask. The second subtask was drawing a line. This subtask simply supported the first, acting as a verification of a sound implementation. The second subtask also had the crucial effect of separating the hands again. Participants performed sequences of the task, with the Toolglass acting as a tool palette from which to select the appropriate colour in the first subtask. After performing this subtask, or the command selection phase of the task, participants entered the second, execution phase and drew the line. Each selection/drawing pair constituted a complete trial.

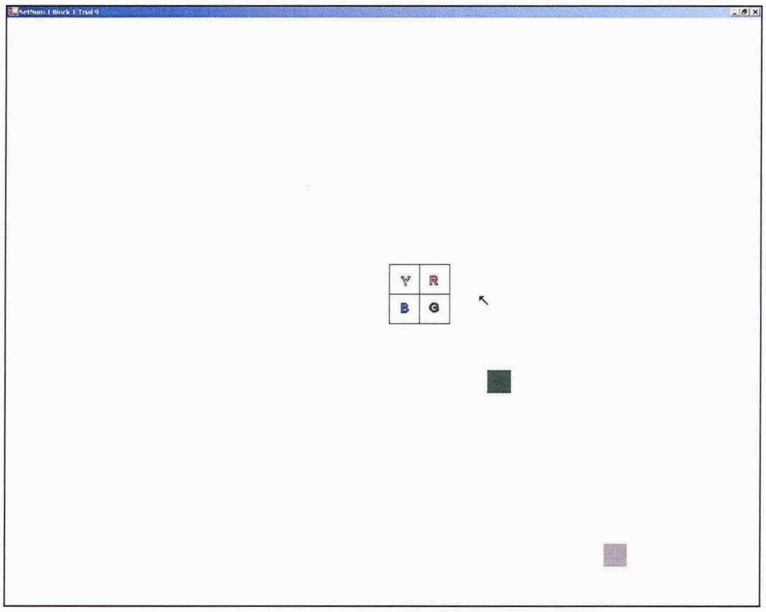
Upon beginning a trial, the display presented two squares to the participant. The squares were differently coloured, with the ending square always grey and the start square either red, green, blue, or yellow. The selections of colours were distributed and determined systematically by software but appeared random to the user. The series was the same for all participants. Also present on the screen were two cursors, one a conventional arrow, pointing north-west and drawn diagonally, and one a Toolglass widget depicted as a palette divided into four quadrants, each with a coloured letter corresponding to the aforementioned colours (Figure 2.1). Figure 3.1 shows the onset of a trial, with the cursors in separate locations.

Figure 3.1: Start of first subtask: the hands are apart. The left hand controls the Toolglass widget and the right hand controls the arrow cursor.



Participants were required to move both hands to the coloured starting square and align the Toolglass quadrant containing the appropriately coloured letter over the coloured square. Figure 3.2 depicts the hands beginning to move to the same location.

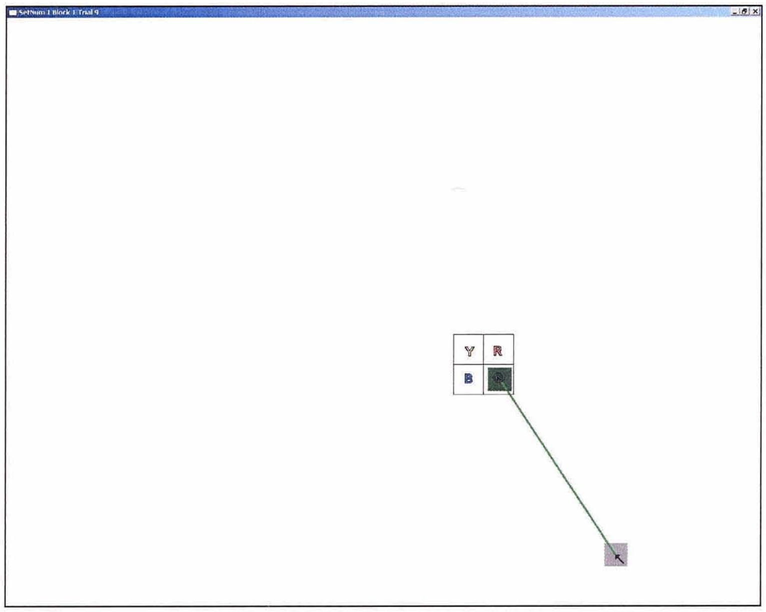
Figure 3.2: First subtask: The hands begin to move to the start square.



With the right hand, participants clicked in the aligned section of the Toolglass to choose the correct colour.

Using the same hand that selected the colour, participants were then to draw the line from the coloured square to the grey square, again clicking the right side device's button to end the trial. Figure 3.3 shows the interface as the line drawing subtask is in process.

Figure 3.3: The second subtask where a coloured line is drawn.



Upon completion of the line, the squares and line would disappear, leaving the participant with a blank screen and the two cursors.

The Kinematic Chain theory predicts that the movement of the cursors would follow Guiard's reference principle. The non-dominant hand, controlling the Toolglass widget, was expected to be moved first towards the start square to perform the colour selection, with the dominant hand then moving into its reference frame to execute the line draw. However, to investigate the resilience of the reference principle with force present, the experiment involved a condition where I hoped users would switch hand movements so that the dominant hand moved into the reference frame of the non-dominant. In this condition, the task would have been easier accomplished if the user moved the dominant hand first and had the non-dominant hand follow.

The display was a two dimensional one. As such, users could freely move in all three dimensions available to the haptic device, but only the x and y values were used by the software. A natural mapping was employed, with the subject's movement of the device up or down resulting in cursor movement in the same direction; similarly for left and right movements.

Minimal revisions from that of Dillon et. al. (1990) were made to the task. In the task of Dillon et. al. (1990) and adopted by Sze (2003), the end square from the previous trial became the start of the next trial with only the new end square in a different location. However, in the present task, both squares of a new trial were in completely different locations. Each trial began with only the Toolglass widget and arrow cursor visible. Participants were required to click a button, either on the left or right haptic device to begin a trial, at which point a new pair of squares would materialize in a different and controlled position from those of the previous squares. Once the participant successfully drew the coloured line, said line and its corresponding squares would be erased from the screen. This resulted in a more realistic user interface experience. Additionally, continuously displaying all connected squares of a particular block of trials was deemed chaotic and sometimes confusing. If the subject chose an incorrect line colour, the line would not be drawn, further simplifying the display. At all times the user interface presented was an uncluttered one upon which the user would complete the next trial. The system recorded data only when the trial began, or after the button click. Apart from the simplicity of the interface, this gave the participants a chance to rest and to proceed at their own pace.

3.3 Protocol

Participants first read a written instruction sheet summarizing the experiment, and signed a consent form. After completing a background questionnaire, participants were given a brief introduction and explanation of haptics if their background knowledge in the area was non existent. Participants were then introduced to the haptic devices and shown how to grip the stylus. Verbal instructions describing the task and interaction technique were given to each participant. To ensure all received the same directives, a written sheet of verbal instructions was used by the examiner as a guide. Participants were instructed to be as fast as possible, while still being somewhat accurate (see Appendix, page 56 for exact instructions).

The experiment consisted of three sets of five blocks of 20 trials. Each block had the same average difficulty as the others in its set. This was achieved by ensuring that distances to targets were equivalent across the blocks. Participants were allowed to take short breaks after each trial. Each set had a different combination of force presence, either no force (NF), force in the left hand (FL), or force in the right hand (FR). To achieve the FL effect, force was enabled in the haptic device in the left hand and disabled in the device in the right hand. The opposite method was used to achieve the FR effect. The order of inclusion of force feedback was counterbalanced across participants.

The choice of clicking the left or right button to start a trial was also counterbalanced across participants. For instance, some participants may have started with force feedback present in a the left hand, needing to press the left button to begin a trial, while others may have started with no force feedback at all and needing to press the right button to begin a trial. The decision to vary the click to start the trial was made to equalize any subconscious priming of either hand. I thought that movement would be primed towards the hand that was doing the clicking (i.e. if a participant was clicking with the right hand to start a new trial, they might subconsciously move the right hand first to accomplish the task).

With the presence of the examiner, participants were required to complete a practice round of 12 trials before each set. Participants were required to notify the experimenter upon completion of every test set. In these sets, the experimenter demonstrated the haptic ability by controlling the force disabled device and letting the user gently hold the force enabled device to experience the pull effect. Participants were then allowed to practice the movement while completing the practice round. After every set, participants filled out a NASA-TLX form. Subjective evaluations were completed at the end of the session. Sessions lasted approximately one hour. The testing took place in the experiment room of the Graphics, Usability, and Visualization (GrUVi) lab at Simon Fraser University.

3.4 Participants

This study had 12 participants (5 female, 7 male), aged 20 to 29 years, with a median age of 26. All participants were right-handed and 11 reported using a computer 14 or more hours weekly. Recruitment was done by mass e-mailing lists of the Computing Science department at Simon Fraser University. No participants had more than trivial experience with haptic interfaces, with only two reporting any experience at all. Eleven participants reported at least 20/30 vision, wearing corrective lenses if necessary. This vision strength was sufficient to readily see the stimuli. One participant was legally blind but held the necessary vision to complete the tasks. Participants were reimbursed $20 for their time.

3.5 Implementation

3.5.1 Hardware

The experiment was run on a Sony Vaio laptop with a Mobile Intel Pentium 4 3.06GHz processor and 512MB of RAM running Microsoft Windows XP Professional 2002, Service Pack 2. Connected to the laptop and employed for the experiment was a 17" TFT LCD monitor with a resolution of 1280x1024.

Two PHANToM Omni (SensAble Technologies, Woburn, MA) haptic devices served as input and force feedback devices. The haptic devices, configured for dual functionality, were coupled to the laptop with an i.LINK firewire (IEEE 1394) connector. Due to the task being a two dimensional one, implementation included only two degrees of freedom (DOF), though the Omnis are capable of three. The Omnis were appropriate for the task, though not uniquely so. Capable of continuously sustaining 3 Newtons of force, the Omnis met and exceeded the requirements for the task. The Omni device includes a moulded-rubber, pen-like stylus with two buttons atop for grip. Subjects grasped an Omni in each hand, usually holding the stylus in a tripod grip (like a pen) with one finger over one of the buttons on the stylus.

3.5.2 Software

The experimental interface was developed using Microsoft Visual C++ .NET 2003 and SensAble's OpenHaptics toolkit. No other applications were running during the experiment. Data were recorded in simple text files. Task completion time and accuracy were recorded for the first subtask of moving both hands to the start square and selecting the colour. For completeness, the time to draw the line, or to complete the second subtask, was also recorded. Incorrect clicks were recorded, with the software recording the number of times a participant chose the wrong colour, clicked outside of the palette, or clicked when the palette was not over the start square. Cursor movements were recorded approximately every 16 ms.

3.5.3 Basic Haptic Rendering

The haptic rendering refresh rate was 1000 Hz. A simple force to distance relationship calculated the force applied to the device during the force feedback part of the experiment. Specifically, the force *(f)*, measured in Newtons, was the difference in distance, measured in pixels, from one cursor's position *(d1)* to the other cursor's position *(d2)*: f = (d2 - d1). The resulting force vector was then normalized, for a maximum force of 1 Newton, if the cursors were not within 18mm of each other. When this 18mm boundary was crossed, the force was ramped down to zero for a smoothing effect.

The overall effects of these forces can be described as a slight pull of the user's arm by the force enabled device. As long as the cursors were in different locations, subjects felt a small but noticeable pull from one cursor toward the other. When both cursors were in the same position, there was no force as the difference in distance between cursors would be zero. Essentially, this resulted in one cursor 'following' the other. Ideally, the user could move both cursors around the screen with very little effort from the hand receiving force feedback. Force feedback was present only for the duration of the first subtask. Once the subject commenced drawing, the force was disabled, allowing them to draw the line and complete the second subtask without the force constantly pulling them back to the other cursor's position.

3.6 Dependent Measures

Measure of success in this project was primarily based on participant performance in the first subtask: colour selection time and accuracy of colour selection. The documentation of missed targets and incorrectly selected line colours aided in determining the accuracy of colour selection. Tracking all cursor movements allowed determination of the labour division of each hand. To obtain subjective views of the experiment and to determine preference of task with or without force feedback, questionnaires were used. The questionnaires consisted of open ended questions to determine the user's perception of advantages and disadvantages of the various conditions. Workload was determined by the NASA-TLX method in which participants self-rated overall workload in terms of *mental demand, physical demand, temporal demand, performance, effort,* and *frustration.*

3.7 Hypotheses

I hypothesized that force feedback would indeed decrease selection time, lessening the workload on a user. Selection accuracy should not have been affected. I hypothesized that contradicting Guiard's principle may allow the user a natural shift in habit from moving akin to the reference principle to moving the non-dominant hand into the dominant hand's reference frame. Selection time and accuracy should not be hampered by this break of habit and may be perceived as natural or comfortable to the user.

4: RESULTS

4.1 Introduction

Surprisingly, force cues to the hands did not seem to be effective compared to no-force cues. Whereas Sze (2003) found an 8% improvement, on average, participants in this study showed no conclusive evidence of improvement in selection times with force feedback present in either hand. However, most indicated a subjective preference for the presence of force and many perceived an improvement in their performance. This section outlines these findings and presents analyses of the data.

4.2 Data Pruning

No individual trials or entire participant datasets were deleted due to system problems, early termination, misunderstanding of instructions, or any other reasons.

4.3 Data Processing

Gross outliers, defined as selection times lying three times more than the interquartile range above the 75th percentile (a threshold of 5.037 s), were identified and omitted. Upon the removal of 39 outliers in total, the remaining values were plotted on quantile-quantile (QQ) plots and observed to be far from normally distributed. We verified that the QQ plots for log-transformed selection times linearized the curved point patterns we observed in the raw QQ plots. Consequently, log-transformed selection times were used in all further computations.

All within-subjects ANOVA tests were first screened for sphericity using Mauchly's test. If the test was significant, the Hyun-Feldt correction was used on the ANOVA degrees of freedom. The performance of the legally blind participant was comparable to all other participants.

4.4 Analysis Method

Data were analyzed using Analysis of Variance, or ANOVA, to examine if treatment variability was significantly greater than error variability of scores within treatments. Each ANOVA was done within-subjects over the last three blocks of a set as these blocks were determined as those in which learning appeared to have stopped. This observation of learning is depicted in Figure 4.1. ANOVA was done on the means for each participant for each condition of the log-transformed trial.

4.5 Results

4.5.1 Effects of Technique

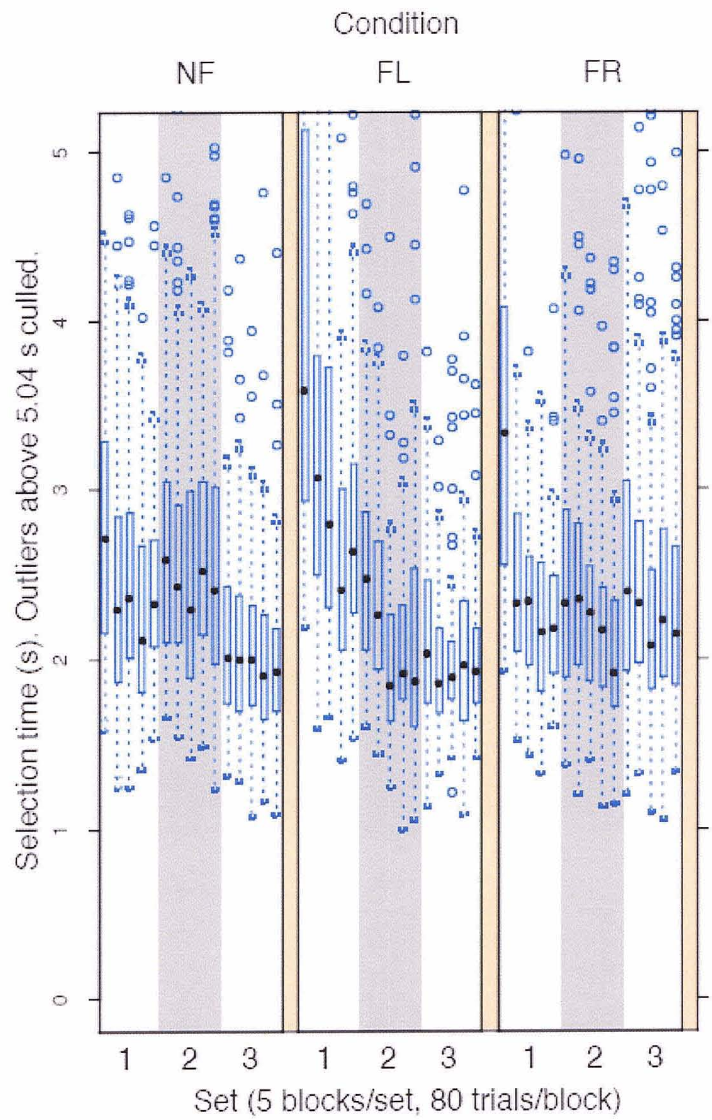
The mean selection times for the techniques were: 2.32 seconds for NF, 2.33 seconds for FL, and 2.28 seconds for FR. Selection time for interaction technique had only a tiny effect (0-2% difference in response times amongst the techniques), far smaller than the variation of the data (95% confidence intervals on the effect sizes from -11% to +13%). Analysis of variance found no significant effect ($F(2, 22) < 1$, *ns*), indicating insufficient evidence for the hypothesis that force feedback in either hand would change selection time.

Draw time had a significant Mauchly sphericity test, so Hyun-Feldt modifiers applied to the degrees of freedom. The effect was not significant ($F(1.5, 16.4) = .29$, *ns*).

Selection accuracy was measured by the number of errors users committed by either choosing an incorrect colour or clicking outside the target, χ^2 (N =2121, df = 2) = 2.82, p = .24. The total number of errors over the last 3 blocks was: 22 for NF, 32 for FL, and 34 for FR.

Learning rates for the three techniques are depicted in Figure 4.1, a graph of the selection times by set. As participants completed more blocks in a set, selection time noticeably decreased, suggesting that they were learning and adapting to the task and technique and therefore performing faster. Users may have been continuing to learn the FR technique, even to the last block of the experiment, and did not achieve the same level of performance as users of the other techniques. Figure 4.1 further suggests that the selection times may be different for the three techniques in the last block. A between-subjects F test was not significant, however: $F(2, 9) = 1.40$, $p = .30$.

Figure 4.1: **Box plot of learning rates for the three techniques. The black circles within the blue outlined rectangles indicate the median selection time for a block. Selection time decreases as block number increases, indicating the participants get better with time. Each set of blocks for each technique depicts the selection times for four participants.**



Subjective workload also showed no significant effect ($F(2, 22) = .36$, *ns*). The mean NASA-TLX scores are presented in Table 4.2.

Table 4.1: Average NASA-TLX scores for the three techniques.

Technique	Score	Standard Deviation
No Force	35	18
Force Left	36	23
Force Right	32	18

Preference data of the 12 participants showed 5 indicated a preference for force feedback in the left hand and 6 for force in the right hand. Only one participant reported a preference for no force, but commented that force was helpful sometimes.

In an open-ended question, participants were asked to *"Briefly describe the disadvantages and disadvantages for each type of interaction."* Most participants perceived force to be less demanding, physically and mentally, allowing them to rest one arm and letting the other one do all the work. Most felt that the no force condition was physically tiring as movement in both hands was consciously required. Of the 11 participants that preferred force, 8 preferred the force they were first introduced to. Accordingly, most reported feeling fatigued when it came time to work with force in the opposing hand. Of the 4 participants who started the experiment with no force feedback, all indicated a preference for force in the left hand, regardless of which force condition they were introduced to first. Participants were also asked to *"please give any other general comments you may have."* Four participants who preferred force feedback indicated that it took time to get used to. One commented with absolute certainty that, given more practice and time to acclimatize, he would be much faster with force in the left hand, the condition that contradicted Guiard's reference principle.

Preference rankings showed that participants who began the experiment with force in the right hand all indicated a preference for said condition. This preference was matched by their workload ratings, which showed 31 for force in the right hand and 38 for the no force condition. The participant group given force in the left hand as a starting condition were split in force preference. The two who preferred force in the left hand reported average workload scores of 26 for no force and 17 for force in the left hand. The remaining two showed no difference in workload between their preferred condition of FR and NF. Of the four participants given the condition of no force as the starting condition, workload perceived dropped from 32 in the no force condition to 20 in their indicated preference of force in the left hand. The sole participant who preferred no force feedback reported 46 for no force and 52 for both force conditions individually.

4.6 Path analysis

A collection of all cursor movements was recorded to keep track of participants' movement paths. This collection noted pixel locations as participants moved the cursors around the screen. Randomly choosing 4 participants, I looked at the path data collected for the NF condition. By looking for the first hand that had a large change in pixel location, I was able to ascertain that 3 participants moved their left hand first in the NF condition.

Due to time restraints and the complexity of the path file, no analysis was done on the FL and FR conditions.

4.7 Discussion

Contradicting the results found in Sze's work (2003), the hypothesis that force improved selection time was not verified. Objective measurements showed no difference between techniques, but user preference showed a difference. Four participants believed that faster performance on their part was possible with more practice in the force feedback conditions. This indicates that force feedback may provide an effective cue in bimanual human-computer interaction with enough practice. Additionally, participants indicated a strong liking for the force feedback and this is vital in human-computer interaction as users should enjoy working with their interfaces. Looking at the responses to the open-ended questions, participants indicated "less effort needed" in the force conditions. This perception of ease of use is also instrumental in HCI. People are far more willing to utilize an interface that they perceive is easy to use.

FL is an interesting condition because users would likely be penalized if they moved in their habitual way according to Guiard's reference principle. If users had in fact been moving the non-dominant left hand first, the force acting on the left hand would have been pulling them back towards the lagging right hand, causing an increase in selection time. I hypothesized that participants would switch from the habitual movement pattern by moving their dominant hand first, resulting in lower selection times in the FL condition than in NF. Though there was no decrease in selection time, there was also no increase when participants were to move in a way contradictory of the reference principle. As such, it seems that force feedback did cause a break in the long standing habit of having the non-dominant hand lead the dominant hand.

Data collected to determine the presence of Guiard's reference principle effects included aggregate completion time of the selection-and-draw task, aggregate workload across conditions, and path analysis. A brief analysis of the path data determined that at least 3 participants were indeed leading with their non-dominant hand, as predicted by Guiard's model. However, participants were not significantly faster in FL or FR. Perhaps analyzing the other effects to determine movement based on Guiard's reference principle would yield more insight and give more pronounced evidence of whether participants adapted and easily switched their role assignments.

Rather, based on subjective preferences, it seems that the choice of roles was highly dependent on the order of force condition introduced. In most cases, participants initially shown FL preferred FL and those initially shown FR preferred FR. This seems fitting as humans are such habitual creatures.

Unfortunately, the results collected in this study cannot suggest answers to the fundamental questions of using haptics in bimanual HCI. Rather, a discussion of changes to this and future experimental protocols may result in significant improvements in selection time. Limitations in learning the task, learning the techniques, asymmetric transfer, and lack of strategies have been identified as contributors to the dismal results. Additionally, there may have been a problem with using coloured letters for the Toolglass. These issues will be discussed in the next section.

5: CONCLUSION AND FUTURE WORK

5.1 Conclusion

Although there are many initial reasons to believe that force feedback would improve human performance in a bimanual pointing task, this study's results showed no significant improvement. To explore the idea of adding force feedback to the ever present visual feedback in bimanual human-computer interaction, the experiment tested three interaction techniques: no force feedback, force feedback in the left hand only, and force feedback in the right hand only. Though empirical evidence showed no significance difference in any of the three techniques, subjective views for most participants showed a preference for force feedback over no force feedback. This observation indicates some benefits to the incorporation of force into bimanual computing for future research. I believe the hypothesis could still hold true as results did not show a significant decrease in performance. There may have been some limitations in the experimental protocol.

5.2 Future Work

Consequent to the empirical results of the user study, there may have been some limitations in the experimental protocol that confounded a real effect in user performance. In the future, I intend to conduct a second user study, delimiting said shortcomings.

To learn the technique, participants had to determine what to attend to and how to move their two hands with the combination of force/non-force. Of the twelve participants, none had more than trivial experience with haptic interfaces and only two reported any experience at all. The participants had no experience with the PHANToM Omnis, let alone with the type of force feedback applied in the experimental software. Many participants commented that they needed more practice with the force and many were confident they would be much faster with this practice. Results suggested that participants were still learning the force in the right hand technique right up to the last block of trials, as shown in Figure 4.1. These effects could be overcome by increasing the number of blocks tested in each technique. Additionally, using a force feedback mouse might yield better performance as users are so accustomed to the regular mouse. In the future experiment, I intend to increase the number of blocks, but continue using the Omnis. No participant indicated any type of fatigue, so a slight increase in trials should be acceptable.

Learning the task may have been a confounding factor, especially when combined with learning the technique. Participants got better at the select-and-draw task over trials. Some of this learning may have continued as participants advanced to different techniques. For those participants beginning with the FL or FR conditions, this task learning was combined with learning the technique, making the condition more difficult. Again, increasing the number of blocks will help offset this effect.

Developing a strategy to take advantage of the force was crucial to effectively complete the pointing task, but participants were taught none. While they were introduced to the devices and the force, they were otherwise purposely uninformed and unassisted. While this omission was intentional to determine whether users would naturally use the force feedback, I now believe that it could have had a major impact on the study. With such a novel sense as that provided by the force "pull", clearer instructions and strategies should have been taught to the participants. In future experiments, I will show them specific strategies to get the optimal performance from the force hand coupled to the movement of the non-force hand. This might include explicitly telling the participant that if they only move one hand, the other will follow so it might be more effective to just move one hand quickly to the desired location.

There appeared to be a disadvantage in using a within-subjects design. There seemed to be large carryover effects from doing one technique before another, as results showed that participants who began with no force feedback performed better in the force feedback techniques. I believe that, after learning the basic task and experiencing the workload and difficulties of the task with no force, participants were better able to judge and adapt to the benefits of having force feedback, thereby performing their selection task faster. Conversely, those who started with a force technique learned the task in the presence of force and had difficulties transferring to a technique with force on the other hand or no force at all. Users also showed a preference for the force they were first introduced to, which implied that it was difficult for users to adapt to a different force technique after learning the first. These effects may not be symmetric and, consequently, learning and technique are strongly confounded. These results indicated confusion of learning and prior technique. There was too much variation to attribute causality. This is an open problem in which adopting a between-subjects design may be less problematic.

The use of coloured letters to represent colours may have been problematic. In demonstrations of the experimental software, some people reported difficulties, saying that they were reading the letters instead of using the shades to denote the appropriate colour. This resulted in confusion and the user taking longer to complete the task. None of the actual experimental participants mentioned this, but it is worth looking into. Perhaps using pure colour swatches instead of letter swatches would result in faster colour selection.

I plan to conduct another user study in the near future to determine if correcting these limitations in the initial experimental protocol will produce a significant effect of having force feedback in bimanual HCI. This new experiment will include more blocks of trials in each condition to curtail the effects of learning of the task and technique. All participants will be shown strategies for working with the force feedback. This should help participants better adapt to and understand how to use the novel feel of the force display. I will consider using a between-subjects design to overcome the asymmetric effects of the within-subjects design. Additionally, I will explore the idea of using pure colour swatches in the Toolglass quadrants instead of coloured letters. With these improvements to the experimental design, a more profound effect of force feedback on bimanual human-computer interaction may be discovered.

APPENDIX: USER STUDY FORMS

User Study Information for Volunteers - June 2006

Name of Experiment Force in bimanual interaction
Investigator Names Adelle Knight, Ted Kirkpatrick
Investigator department School of Computing Science, Simon Fraser University

Risks
You take no reasonably foreseeable risks if you volunteer. You will be using a computer. You will be able to take breaks at regular times. If you start, you will be free to stop the session at any time.

If you are a student: your grade, scholarship, and other academic benefits will not be affected by whether you volunteer, and if you volunteer, whether you complete the session.

If you are employed by the university, or by a faculty member as a research assistant: your pay, benefits, and any future recommendation letters will not be affected by whether you volunteer, and if you volunteer, whether you complete the session.

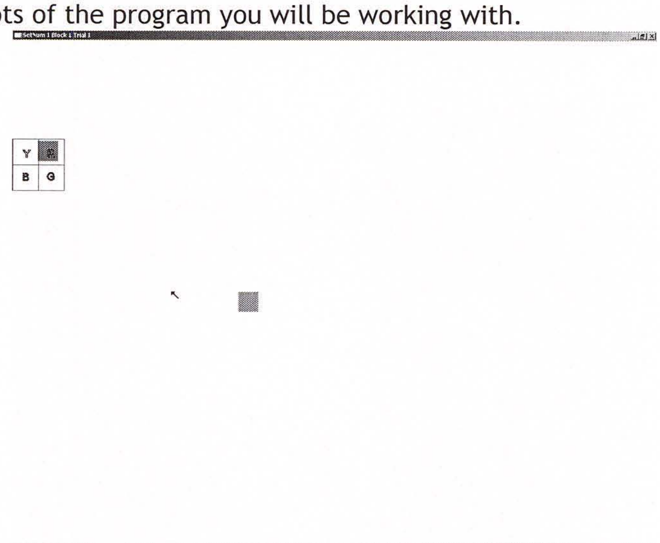
Benefits
You will be helping develop faster, more comfortable and more enjoyable ways of working with computers.

Confidentiality
Results of this study will be published in scientific papers, and made available on the Internet and other public forums. However, your identity will not be recorded. All the data will be filed under a numeric code assigned to you only for this study, and there will be no way that you will be identifiable or that anyone (including us) can link your data to you. Your signed consent form will be kept separate from the data.

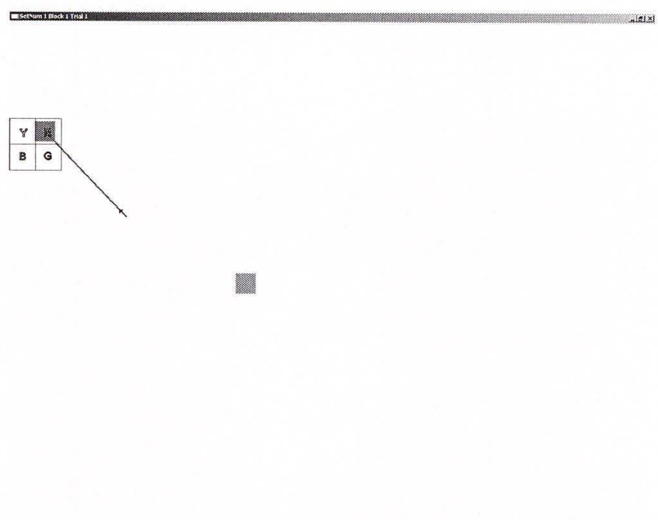
What We Will Ask You to Do
This study tests several methods of drawing coloured lines between two squares. Each such method is referred to as an *interaction technique*. While you work, the computer will record how you moved your hands, and afterwards we will analyze the way you moved. Please do the activity as quickly as you comfortably can, while still being accurate. Some conditions may be more difficult than others. Do the best you can.

Activity
Two squares will appear on the screen, one grey and the other coloured red, blue, green, or yellow. Two cursors will be visible, one a regular arrow and one a palette divided into four quadrants, each with a coloured letter corresponding to the above colours. You must move both hands to the coloured dot, and then, with the hand commanding the arrow cursor, click in the section of the palette whose colour corresponds to the dot's colour. Using the hand controlling the arrow cursor, draw the line from the coloured dot to the grey dot. As soon as you complete the line, the two squares will disappear, leaving you with a white screen and the two cursors. Each such instance of this activity is called a *trial*. You will complete about 300 trials. To begin a new trial, click the button on the device in your left hand.

Below are screenshots of the program you will be working with.



Screen 2: Moving to target square.



Screen 2: Drawing red line.

Overall Flow of the session

For each interaction technique, you will go through three stages:

1. *Practice.* We will show you how the technique works, then you will complete 12 practice trials.

2. *Main Blocks.* You will complete five *blocks* of trials, with 20 trials in each block. You may rest in between trials and/or after each block. After each block is complete, a window will appear telling you to notify the experimenter. Please do so.

   If you need to rest or you have a question, please wait until **after** you've finished a trial or block.

3. *Workload Questionnaire.* After completing each interaction technique, you will complete a brief questionnaire measuring how difficult you perceived the technique to be.

Background Information

Before starting the experiment, we'd like to know some general information, and how much experience you have had with techniques related to the ones in this study.

Age: ____ **Gender:** Female ___ Male ___

Level of Education (including current program of study):

High School ___ Bachelor's ___ Master's ___ Doctorate ___

Which hand do you prefer for using the mouse? Right ___ Left ___

About how many *hours a week* do you use a computer?
Less than a half-hour ___
Less than 2 hours ___
Less than 7 hours ___
Less than 14 hours ___
14 hours or more ___

Do you have at least 20/30 vision (wearing corrective lenses if necessary)?

Yes ___ No ___

How much have you used the following input methods or software?

	Never	Once or twice	Some, but not regularly	Every week	Every day
Mouse					
Point-force haptic devices such as the Phantom					
Two handed pointing (such as a mouse in both hands)					
Two handed pointing moving both hands to the same location.					

NASA-TLX Workload Questionnaire

We'd like to ask you about how difficult you perceived the task you just completed to be. Please answer the questions below by marking an X in the appropriate box in the provided rating scales.

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?

Low **High**

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?

Low **High**

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?

Low **High**

How hard did you have to work (mentally and physically) to accomplish your level of performance?

Low **High**

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?

Good **Poor**

How insecure, discouraged, irritated, stressed and annoyed versus secure, gratified, content, relaxed and complacent did you feel during the task?

Low **High**

Importance of Different Workload Categories

Please select the member of each pair that had the more significant effect on the overall *workload* for all the tasks performed in this study:

Physical Demand	☐	or	☐	Mental Demand
Temporal Demand	☐	or	☐	Mental Demand
Performance	☐	or	☐	Mental Demand
Frustration	☐	or	☐	Mental Demand
Effort	☐	or	☐	Mental Demand
Temporal Demand	☐	or	☐	Physical Demand
Performance	☐	or	☐	Physical Demand
Frustration	☐	or	☐	Physical Demand
Effort	☐	or	☐	Physical Demand
Temporal Demand	☐	or	☐	Performance
Temporal Demand	☐	or	☐	Frustration
Temporal Demand	☐	or	☐	Effort
Performance	☐	or	☐	Frustration
Performance	☐	or	☐	Effort
Effort	☐	or	☐	Frustration

Category definitions (these are the same as the ones on the ratings screen)

Mental Demand	How much mental and perceptual activity was required (such as thinking, deciding, calculating, remembering, looking, or searching)? Was the task easy or demanding, simple or complex, exacting or forgiving?
Physical Demand	How much physical activity was required (such as pushing, pulling, turning, controlling, or activating)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or labourious?
Temporal Demand	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	How hard did you have to work (mentally and physically) to accomplish your level of performance?
Performance	How successful do you think you were in accomplishing the goals of the task? How satisfied were you with your performance in accomplishing these goals?
Frustration Level	How insecure, discouraged, irritated, stressed and annoyed versus secure, gratified, content, relaxed, and complacent did you feel during the task?

Opinion Questionnaire

Now that you've completed the experiment, we'd like to ask you a few questions about what you experienced.

Which type of feedback did you prefer?

No force ___ Force in Left hand ___ Force in Right hand ___

Briefly describe the advantages and disadvantages for each type of interaction:

a) No Force

Disadvantages:

____

____

____

Advantages:

____

____

____

b) Force in Left Hand

Disadvantages:

____

____

____

Advantages:

____

____

____

c) Force in Right Hand

Disadvantages:

____

____

____

Advantages:

____

____

____

Finally, please give any other general comments you may have

VERBAL INSTRUCTIONS

WITHOUT FORCE

In whatever way is comfortable for you, move both cursors to overlap the coloured dot. You may move one hand at a time or both together.

When both cursors are over the dot, use the *(right/left)* hand that controls the arrow cursor to click inside the quadrant of the palette to match the coloured letter with the colour of the dot.

Once you have selected the correct colour, the same coloured line will appear. If you selected the incorrect colour, no line will be drawn. Simply re-click in the appropriate colour and continue.

Now, draw the line by moving the arrow cursor to the grey dot.

Once you are over the grey dot, click the button to complete the trial.

You may rest or proceed to the next trial by clicking the left mouse button.

You must now complete a practice round of 20 trials. I will stay here to answer any questions or to help you, should you need it.

WITH FORCE ON

(if participant starting with force, read first 3 paragraphs)

I will activate the force in the haptic device. When the two squares are on the screen, you will feel a *pull* towards the other cursor. The closer together the cursors are, the less force you will feel. When you make your colour selection, you will feel no force and will be able to easily complete drawing the line.

Lightly hold the haptic device handle and I will demonstrate. (Participant holds OMEGA and I move device around).

You may now complete a practice round of 20 trials.

SWITCHING FORCE

Now, I will switch the force in your hand. You will feel the pull in your other hand. Let me demonstrate....

TRIALS

You may now go ahead and complete a block of test trials. This will consist of 25 trials. After the block, a window will pop up asking you to notify me. Please do so. Do not click OK.

REFERENCE LIST

Balakrishnan, R., & Hinckley, K. (1999). The role of kinesthetic reference frames in two-handed input performance. *Proceedings of the 12th annual ACM symposium on User interface software and technology.* November 07 - 10, 1999, Asheville, North Carolina, USA. pp. 171-178.

Beaudouin-Lafon, M., & Lassen, H.M. (2000). The Architecture and implementation of CPN2000, a post-WIMP graphical application. *Proceedings of the 13th Annual ACM Symposium on User Interface Software and Technology.* 2000, San Diego, California, USA. pp. 181-190.

Bernstein, N.L., Lawrence, D.A., & Pao, L.Y. (2003). Design of a uniactuated bimanual haptic interface. *Proceedings of the 11th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems.* 2003. Washington, DC, USA. pp. 310-317.

Bier, E.A., Stone, M.C., Pier, K., Buxton, W., & DeRose, T.D. (1993). Toolglass and Magic Lenses: The see-through interface. *Proceedings of the ACM SIGGRAPH 93 Computer Graphics Annual Conference Series.* August 1993, Anaheim, California, USA. pp. 73-80.

Buxton, W., & Myers, B.A. (1986). A study in two-handed input. *Proceedings of the ACM CHI 86 Human Factors in Computing Systems Conference.* April 13-17, 1986, Boston, Massachusetts. pp. 321-326.

Dennerlein, J.T., Martin, D., & Hasser, C. (2000). Force-feedback improves performance for steering and combined steering-targeting tasks. *Proceedings of the ACM CHI 2000 Human Factors in Computing Systems Conference.* April 1-6, 2000, The Hague, The Netherlands. pp. 423-429.

Dillon, R.F., Edey, J.D., & Tombaugh, J.W. (1990). Measuring the true cost of command selection: Techniques and results. *Proceedings of the ACM CHI 90 Human Factors in Computing Systems Conference.* 1990, Seattle, Washington, USA. pp. 19-25.

Guiard, Y. (1987). Asymmetric division of labor in human skilled bimanual action: The kinematic chain as a model. *Journal of Motor Behavior, 19* (4), 486-517.

Guiard, Y., & Ferrand, T. (1996). Asymmetry in bimanual skills. In D.Elliot, & E.A. Roy (Eds.), *Manual Asymmetries in Motor Performance* (pp. 175 – 195). New York: CRC Press.

Guimbretiere, F., Martin, A., & Winograd, T. (2005). Benefits of merging command selection and direct manipulation. *ACM Transactions on Computer-Human Interaction, 12*(3), 460 – 476.

Hinckley, K., Pausch, R., Proffitt, D., Patten, J., & Kassell, N. (1997). Cooperative bimanual action. *Proceedings of the ACM CHI 97 Human Factors in Computing Systems Conference*. March 22-27, 1997, Atlanta, Georgia, USA. pp. 27-34.

Kabbash, P., Buxton, W., & Sellen, A.J. (1994). Two-handed input in a compound task. *Proceedings of the ACM CHI 94 Human Factors in Computing Systems Conference*. April 24-28, 1994, Boston, Massachusetts, USA. pp. 417-423.

Kurtenbach, G., Fitzmaurice, G., Baudel, T., & Buxton, B. (1997). The Design of a GUI paradigm based on tablets, two-hands, and transparency. *Proceedings of the ACM CHI 97 Human Factors in Computing Systems Conference*. March 22-27, 1997, Atlanta, Georgia, USA. pp. 35-41.

Oakley, I., Adams, A., Brewster, S.A., & Gray, P.D. (2002). Guidelines for the design of haptic widgets. *Proceedings of British HCI 2002*, 2002. 16 pages.

Oakley, I., Brewster, S., & Gray, P. (2001). Solving multi-target haptic problems in menu interaction. In *Extended Abstracts of Proceedings of the ACM CHI 2000 Human Factors in Computing Systems Conference 2001*. pp. 357-358.

Oakley, I., McGee, M.R., Brewster, S., Gray, P. (2000). Putting the feel in 'look and feel'. *CHI Letters*, *2*(1), 415 – 422.

Sze, J. (2003, July-August). Toolglass interaction with visual and haptic feedback of nondominant hand location. [Unpublished data]. School of Computing Science, Simon Fraser University.