Bimanual Computer Input and Forearm Support Implemented and Evaluated in an Integrated System

by

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Abstract

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This work addresses issues in providing more efficient, intuitive, and comfortable input to computer users. These are important problems because the costs associated with poor human-computer interfaces can be very high — ranging from steep learning curves to wasted time and, in the worst case, to disabling injury. An integrated approach to these problems is taken by providing both forearm support and bimanual (or, two-handed) input. Since there are both strong physical and cognitive aspects to this approach, work in this area requires development of both new hardware — to enable new forms of input, and new software — to use these new forms of input in a meaningful way.

On the hardware side, the benefits of forearm support are first explored through an experimental study testing a new forearm support device. This study verifies the benefits of forearm support for a variety of tasks both for reducing upper extremity muscle load and for improving subjective responses. Building on these findings, a new computer input device, called the Command Chair, is presented to provide more ergonomic computer input, including forearm support, while also providing bimanual input.

Following the approach of integration, the Command Chair approach integrates an office chair, keyboard input, bimanual pointer input, and forearm support into a single computer input system. This allows the workstation designer to consider the input system as a whole, rather than as a collection of individual devices. In turn, this allows for better control of body activities and postures, with the goal of providing user comfort over a full workday. This system uses the location of the keyboard to position the mouse, removing the need to switch between devices.

Workstation throughput tests developed for this work are presented in conjunction with conventional pointing tests to quantify the performance of the Command Chair relative to other workstations. Measures from these tests demonstrate that the Command Chair improves user wrist posture and reduces subjective wrist fatigue relative to a traditional input station, but also provides slower input speed - partially attributable to higher system inertia and poor bearing performance.

A new technique to evaluate the tradeoff between improved comfort and reduced efficiency in computer workstations is developed to interpret these results. This technique works by normalizing different metrics of workstation performance to a monetary cost basis. Considering the workstation operating costs as a function of time indicates that the Command Chair is less costly to operate than a traditional computer input station when used for more than thirty four days. This result verifies that the Command Chair provides improved overall workstation performance relative to a traditional computer workstation.

On the software side, a new bimanual software technique is developed to interpret the bimanual input that the Command Chair provides and apply it in meaningful and useful ways. This technique provides a new means of bimanual command selection, and is called "Bimanual Marking Menus." To verify the anticipated performance benefits of this technique, a test environment is used to compare its performance with five other techniques: static toolbars, hotkeys, grouped hotkeys, marking menus, and toolglasses. This experiment builds on previous work by setting the comparison in a commonly encountered task, shape drawing. In this context, grouped hotkeys and bimanual marking menus are found to be the fastest. Subjectively, the most preferred input method is the newly developed technique: Bimanual Marking Menus. Toolglass performance is unexpectedly slow. The results of this experiment verify the speed, usefulness, and potential of bimanual input, and provide a new and powerful technique for its implementation.

As a whole, this work provides evidence supporting the benefits of both forearm support and bimanual computer input. Additionally, this work demonstrates how bimanual computer input and forearm support can be leveraged for improved usability, efficiency, and comfort in human-computer interaction — the ultimate goal of this project.

Professor Paul K. Wright, Chair   Date

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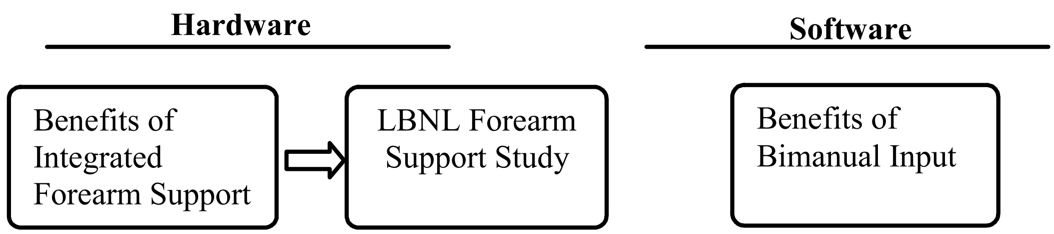
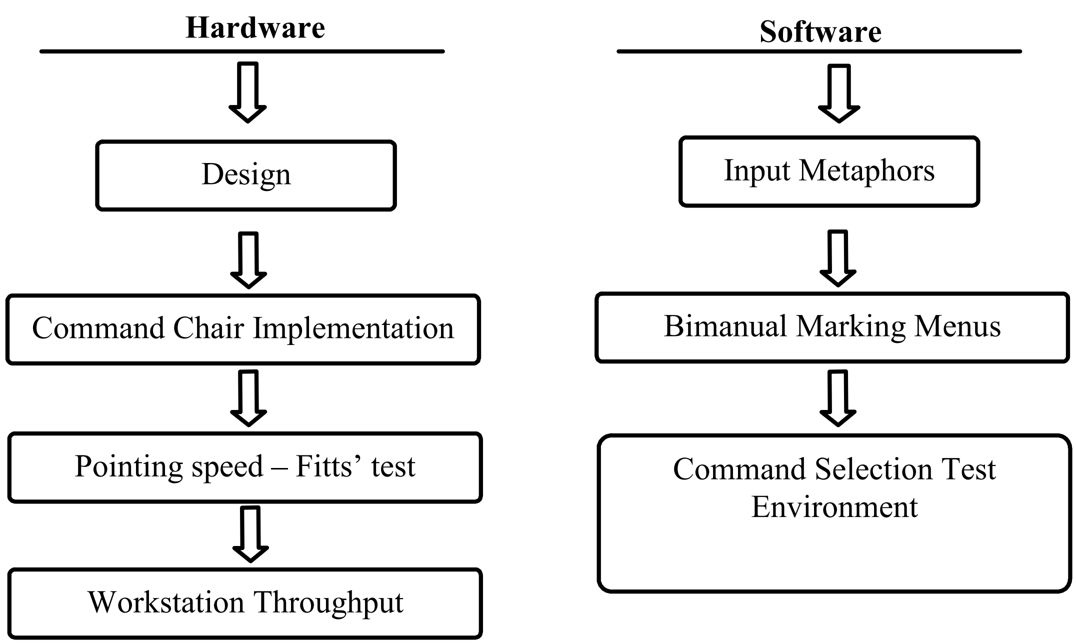
HYPOTHESIS:

Bimanual computer input and forearm support can be leveraged for improved usability, efficiency, and comfort in human-computer interaction.

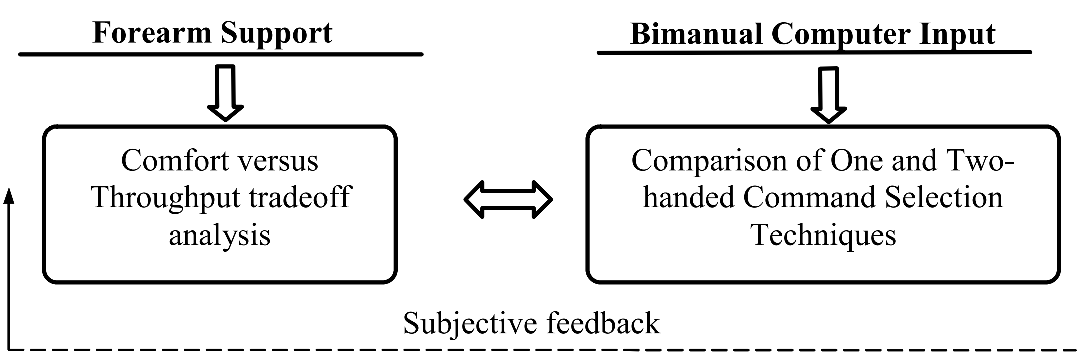
BACKGROUND INVESTIGATIONS:



IMPLEMENTATION AND EXPERIMENTAL METHODS:



HYPOTHESIS VERIFICATION:



The findings support the benefits of bimanual computer input and forearm support for improved usability, efficiency, and comfort in human-computer interaction.

Chapter 1: Introduction - Overview of Some Problems in Computer Input and Some Potential Remedies

1.1 Motivation: Problems with Standard Input Devices and Methods

Despite many advances, today's standard computer interfaces and interface devices are often still non-intuitive, inefficient, and uncomfortable to use. These problems can be quite profound, and often lead to large costs to both individuals and businesses.

1.1.1 Non-intuitive Interfaces and Devices

Non-intuitive interfaces and devices are often a source of frustration, particularly for novice computer users. A large reason for user frustration is that motions and manipulations that are commonplace in the physical domain are not available for virtual manipulations. This means that users must learn new virtual techniques to achieve their goals, rather than being able to use the tools that they are familiar with. Part of this problem is due to the fact the standard paradigm limits data entry to a single two-dimensional pointer and a keyboard.

The costs associated with non-intuitive interfaces show up for users in the form of large learning curves and frustration in having to settle for results that are easy to create with software, not the truly desired results. These software usability constraints can severely hamper user creativity by limiting what they can accomplish. Demonstrating this, a colleague who is an architecture enthusiast claims he can recognize any building designed in AutoCAD® by looking for specific design features that are easy to create using that software.

Devices that are non-intuitive can be equally frustrating to users as non-intuitive interfaces. Learning rates have been shown to differ between different types of input devices (Karat et al., 1986, Douglas et al., 1999), meaning that users can quickly grasp the proper use of some devices, while some require more practice (less intuitive). Some of these differences are due to different mappings between physical input to virtual motions (Card et al., 1991). For example, an input device that maps physical position to virtual pointer position tends to be more intuitive to use than a device that maps the rate of change in force to virtual pointer position. Therefore, maintaining a direct mapping between the controller and display is a very important factor in the creation of an intuitive input device.

1.1.2 Inefficient Interfaces and Devices

Today's current standard input method, *Static Toolbars*, has been shown to be slower than other available forms of input (Dillon et al., 1990, Kurtenbach et al., 1993). This is because the standard toolbar method requires more pointer motions and button clicks than other more recently developed input methods. The user is required to move the cursor back and forth between the work area and the menus, while making selections from each. These extra motions are unnecessary for other interface techniques, such as pop-up menus and hotkeys. The time required for these extra motions can be significant. For example, a recent study found that several complete common tasks require roughly 15% less time to complete using hotkeys relative to static toolbars (McLoone et al., 2003). Not only do these extra motions require more time to complete than other techniques, but they also require more physical motions to accomplish a given task – resulting in more user repetitions, and higher risk for Musculoskeletal Disorders (MSDs).

As with input techniques, there is a range of input speeds for input devices. In general, the mouse is considered to be the fastest pointing device (Card et al., 1978, MacKenzie et al., 1991), followed by the tablet. Many pointing speed issues relate to the issues noted for intuitive input device design, but include other issues as well. Some examples include device inertia, and the musculature involved in manipulating the device. For example, finger controlled isometric joysticks have shown relatively inefficient input speed, due largely to unconscious finger jitter (Mithal and Douglas, 1996). Similarly, the shoulder-actuated 3M *Renaissance* mouse has been shown to provide slower input than a more traditional wrist-actuated mouse (Aaras et al., 2001). Therefore, the selection of input device for a given task can have a dramatic impact on the efficiency with which the task is performed, irrespective of the input technique used.

In addition to pointing time, the time required to shift between input devices (called homing time) can also have an impact on the overall task efficiency. Most tasks require a combination of pointing device and keyboard input. Previous research has studied the relative times spent using these devices for a variety of tasks (deKorte et al., 2003, Johnson et al., 1993). Similarly, the time required to switch between common input devices has also been documented (Card et al., 1980), and was found to be roughly 400 ms to switch from the keyboard to the mouse. Considering that the same study found that average pointing time is roughly 1100 ms, and that average keying time is roughly 200 ms, it is plain to see that homing time can account for a large portion of total task time, depending on the specific requirements of the task and how much device switching is required.

Devices have been constructed in an attempt to minimize homing time, but their inferior pointing efficiency wound up outweighing the benefits of homing time reduction (Douglas and Mithal, 1994). So, homing time remains a source of inefficiency in computer input.

1.1.3 Uncomfortable Interfaces and Devices

More serious than lost efficiency is the epidemic of Musculoskeletal Disorders (MSDs) that result from improper design and use of computer input workstations. These injuries extol high costs not only in dollar amounts, but also in human suffering. Many new approaches to computer input overlook the key need for comfortable input. For instance, many new virtual reality systems require users to wear bulky stereoscopic goggles, or hold their arms in unsupported space while manipulating mechanical haptic armatures (Bullinger et al., 2003). While these systems extend computer input to three dimensional spaces, they are often uncomfortable to use for more than a few minutes.

While advances have been made in reducing injury risk of using conventional input devices (Tittranonda et al., 1999), many problems still persist and injury rates remain unacceptably high. A controlled epidemiological study found an incidence rate of MSDs among new office workers to be 56 upper extremity injuries per 100 workers per year (Gerr et al., 2002). Note that this surprisingly high number does not refer to the number of injured workers, only to the total number of injuries (as many workers suffered multiple disorders simultaneously). Considering that each upper extremity injury leads to an average 12 lost days of work (Bureau of Labor Statistics- BLS, 2000), and costs on average $38,500 for worker’s compensation costs (California Commission on Health and Safety and Workers’ Compensation – CA CHSWC, 2000), it is clear that there is a very strong financial incentive for correcting these problems, in addition to the humanitarian incentive. From a productivity standpoint, worker productivity and effectiveness have also been shown to diminish when workers suffer from musculoskeletal symptoms (Hagberg et al., 2002). All together, the US General Accounting Office has estimated the total cost of MSDs to business to be approximately $20 billion per year.

1.2 Potential Remedy: Integrated Forearm Support

One approach to providing more comfortable computer input is to provide integrated forearm support with the workstation. Forearm support has been shown to correlate to reduced risk of work-related neck and shoulder injuries (Marcus et al., 2002). Several products have been developed to provide forearm support, including the Kinesis Evolution™ keyboard, the Morency rest, the Butterfly board, and the Ergorest® Articulating Arm Support, among others. Additionally, a number of studies have examined the specific effects of forearm support on computer input. These studies have found beneficial effects of forearm support in reducing risk factors for MSDs (such as static muscle loads and posture), as well as subjective comfort.

One study evaluated the Kinesis keyboard, a chair-mounted keyboard, with respect to performance, posture and comfort (Hedge and Shaw, 1996). The device was found to reduce ulnar deviation postures and durations, as well as improve the posture of the neck and shoulders. Postures are important, as extreme ulnar deviation has been correlated to increased risk of MSD (Bach et al, 1997, Hedge et al., 1999). Subjective results were mixed, and typing speed was found to be slightly reduced for the support device, particularly for hunt-and-peck typists.

In addition to looking at postures and subjective feedback, other studies have examined the effects of forearm support on muscle loads during computer input. A study evaluating the effectiveness of arm and wrist supports in reducing the muscle activity of the descending part of the right trapezius muscle was presented by Visser, et al. in 2000. Electromyography (EMG) and qualitative comfort measurements were made for two arm and two wrist support conditions versus a no-support condition for mousing and keying tasks. This work was partially motivated by previous findings (Veiersted, 1994), which demonstrated that prolonged static muscle tension in the trapezius muscle was a risk factor for trapezius myalgia. A significant reduction in muscle activity was found for the arm supports in both mousing and typing tasks, while wrist supports were found to increase muscle activity. However, no subjective difference between the rankings of the five conditions was found, which was partially attributed to the short duration of the study (11 min./task), and the low-intensity nature of the tasks.

Another study comparing fixed arm support and suspended arm support to no support for a keying task with three different angle conditions was presented by Erdelyi et al., in 1988. The output measure was the EMG activity of the upper trapezius. Both support conditions were found to reduce EMG activity, with fixed support showing a more dramatic reduction. Erdelyi's study also found that increasing inner elbow angle reduced muscle activity (supporting the findings of Marcus et al, 2002). Strangely, the condition that was shown to provide the least muscular activity (elbow angle = 105°, fixed support), was ranked as the subjectively least comfortable. This contradiction was not discussed in Erdelyi's paper.

In 1997, Aaras, et al. studied the effects of postural changes on EMG activity in the upper trapezius and erector spinae lumbalis for keying and mousing tasks. One of the postural effects studied was the presence of forearm support from the tabletop. Static load was found to be significantly lower (by almost 400%) in both trapezius muscles, as well as the right erector spinae lumbalis for the forearm support condition of the keying task. Trapezius loads for both left and right side were also significantly lowered with the presence of forearm support for the mousing task. The right erector spinae lumbalis also exhibited reduced activity for mousing with support.

Taken as a whole, these findings provide strong support for the argument that providing forearm support reduces the risk for Musculoskeletal Disorders for mousing and keying tasks while also increasing subjective comfort. These findings are bolstered by the study presented in Chapter 2, which explores the effects of a spring-loaded dynamic forearm support device.

1.3 Potential Remedy: Bimanual Computer Input

People naturally use two hands when performing physical operations, but standard computer interfaces make use of only one pointing device. Research in bimanual (or, two-handed) interfaces has shown that the presence of pointing devices in both hands can lead to more natural and efficient interaction.

Bimanual interfaces can improve **intuitiveness** by:

Enabling more input methods – allowing the body to make virtual manipulations that more closely match physical manipulations.

Enabling more sensory feedback – utilizing a user's innate sense of body awareness (proprioception).

Bimanual interfaces can improve **efficiency** by:

Facilitating parallel input – enabling simultaneous input streams, thereby reducing overall input time.

Bimanual interfaces can improve **comfort** by:

Splitting workloads between two limbs – reducing the load on a single limb.

Providing new body positions and motions – providing more comfortable input.

Past research in this area has focused primarily on improving efficiency and developing new bimanual input techniques using traditional pointing devices. An early study by Buxton and Myers in 1986 demonstrated the potential of bimanual interfacing. Their study required a user to manipulate a square from an initial position to a given target. Translation was performed with a standard dominant-hand (DH) mouse, while scaling was performed with a scaling wheel controlled by the non-dominant hand (NDH). They found that experts of the bimanual system performed 15% better than experts using the one-handed system. As might be expected, they also found that as the percentage of parallel activity (i.e. the time that both hands were moving simultaneously) increased, the time required to complete the operations decreased. This was a seminal study, because it demonstrated the potential benefits of bimanual input for the first time, and spurred interest in this research area.

Since then, several other studies have been performed on bimanual interaction, and several theories have arisen regarding the best ways to implement it. Bimanual input for command selection is discussed in Chapter 6, but several other important studies are worth discussing here.

Several studies have explored drawing and virtual surface generation with two-hands (Sachs et al., 1991, Chatty 1994, Raisamo and Räihä, 1996, Zeleznik et al., 1997, Llamas et al., 2003). One such completely new bimanual drawing environment was developed at Alias® (Kurtenbach et al., 1997). This environment implemented many novel and conventional bimanual techniques – many of which have since been incorporated into Alias' Wavefront software. Unfortunately, high-level design tools are difficult to quantitatively evaluate in order to demonstrate performance benefits relative to traditional devices. This is because they often enable new manipulations for which there is no single handed equivalent.

To address this problem, other studies have focused on constraining bimanual input to a smaller task – allowing for quantitative comparisons to be made between different techniques for a predefined task. A study exploring the benefits of manipulating two-dimensional splines with two hands simultaneously showed significant benefit for the bimanual approach (Owen et al., 1998). This benefit was postulated to be partially due to the fact that two-handed interaction allows for control of more of the curve at once – making spline control vertex manipulation more intuitive.

Bimanual generation of more conventional shapes (such as ovals, rectangles, etc.) has also been explored in the context of graphical cropping (Leganchuk et al., 1998). Here again, the bimanual shape manipulation techniques showed significant benefit over traditional techniques. In particular, the able to manipulate 'stretchable' shapes with both hands simultaneously was found to be much preferred relative to one-handed shape manipulation. Having complete, simultaneous control of the form, position, and scale of a given shape was postulated to be a large part of the reason for the improved performance with the bimanual technique.

The use of the non-dominant hand for virtual camera control in simple rotation and docking tasks has also been studied (Balakrishnan and Kurtenbach, 1999). For three-dimensional target rotation and selection, the two-handed approach was found to be about 20% faster than the comparable one-handed approach, and subjectively more preferred. A three-dimensional docking task showed no initial difference between the one and two-handed input methods. However, as users became more experienced with the system, performance benefits were seen for the bimanual techniques for this task, as well.

While most studies have used traditional pointing devices (particularly tablets, mice, and trackballs), some work has gone into developing new hardware for bimanual interaction. The *Padmouse* was developed as a non-dominant hand (NDH) pointing device with an integrated touchscreen for command selection (Balakrishnan and Patel, 1998). This integration resulted in improved performance and subjective preference relative to conventional input devices. The *Toolstone* is another promising device for bimanual input (Rekimoto and Sciammarella, 2000). Its orientation controls the mode of interaction, while simultaneously providing NDH pointing input. An apparatus for facilitating pre-surgery visualization demonstrated the benefits of enabling proprioceptive feedback to users (Hinckley et al., 1997). Other hardware approaches have also been attempted, with varying degrees of success (Frohlich and Plate, 2000, Hinkley et al., 1998).

1.4 Integration of Bimanual Computer Input and Forearm Support

The approach of the present project is to blend the best of both bimanual computer input and forearm support into an integrated system. Since there are both strong physical and cognitive aspects to this approach, work in this area requires development of both new hardware - to enable new forms of input, and new software - to use these new forms of input in a meaningful way. In addition to providing bimanual input, the hardware development was focused on incorporating ergonomic concepts into the design, with the goal of making the device comfortable to use for a full 8-hour workday and reduce the risk for musculoskeletal disorders.

The course of action to achieve these goals was first to more thoroughly study the effects of forearm support, presented in Chapter 2. Here, a passive support device developed at Lawrence Berkeley National Labs (LBNL) is presented, along with an examination of its effectiveness for a variety of tasks. Chapter 3 discusses how forearm support (and the lessons learned in the LBNL study) was combined with bimanual computer input to generate a new integrated bimanual computer input system. This system is studied and evaluated in chapter 4, and the tradeoffs inherent in the design are discussed in chapter 5. Chapter 6 focuses on the bimanual input and software aspects of the project. In particular, a new bimanual command selection technique is described and evaluated in comparison to a variety of existing one and two-handed input techniques. Finally, conclusions are presented in chapter 7.

Chapter 2: Evaluation of a Dynamic Forearm Support for Seated and Standing Tasks

2.1 Introduction

Low force, static exertion during the performance of hand intensive tasks has been identified as a risk factor for Work-Related Musculoskeletal Disorders (WMSDs) (NRCIM, 2001). For example, Veiersted (1994) found that prolonged static tension in the trapezius muscle was a risk factor for trapezius myalgia. Engineers at Lawrence Berkeley National Labs (LBNL) recently launched a design effort aimed at developing a device to support the upper extremity in order to reduce the static load on the shoulder and forearm muscles for a variety of repetitive, hand intensive tasks.

Repetitive tasks that were identified as potentially benefiting from reduced upper extremity loading are found in many workplace settings including office, manufacturing, assembly, laboratory, quality assurance, and service work. Examples of tasks include computer input, product assembly, pipetting, soldering, and drilling. Previous types of arm suspension and support devices have been developed to reduce muscle load, discomfort, and pain in the neck and shoulder regions (Lintula et al., 2001, Schuldt et al., 1986 and 1987). Arm support seems to reduce loading of the arms and upper shoulder (Aaras et al., 1997, Feng et al., 1997 and 1999), but overall benefit findings have been somewhat mixed, depending on outcome measures. For example, some studies have found muscle load reductions only for particular subjects (Tepper et al., 2003).

Subjective comfort ratings and preferences have also been found to be mixed for arm support (Lintula et al., 2001, Erdelyi et al., 1988).

The effects of providing the new dynamic forearm support device, incorporating a spring-loaded suspension system with a horizontally movable armature – a configuration not previously tested - were studied under a variety of laboratory conditions. One of the goals of the new design was to accommodate a variety of tasks in either a seated or standing posture. The purpose of this study was to determine whether or not the forearm support reduces static muscle activity and improves subjective measures of usability across a variety of tasks. These findings are important to verify the benefits of and assist in the design of forearm support devices.

2.1.1 The Dynamic Forearm Support Device

The dynamic forearm support device is a spring-loaded armrest providing roughly twelve inches of vertical travel, and a horizontal range-of-motion of roughly 25 inches (Figure 2.1.1). Spring support is provided by large torsion springs wrapped around drums. The preload on the springs is adjustable to provide various levels of support at the forearm rest, depending on user preference. Support is commuted through a vertically oriented four-bar linkage constructed of stiff members.

Three rotary joints in the horizontal plane provide planar range-of-motion and allow for motion during reach or shoulder internal or external rotation. The support framework can be adjusted vertically to accommodate a range of user heights. Gel-filled pads are provided on the forearm rests in order to provide comfortable support.

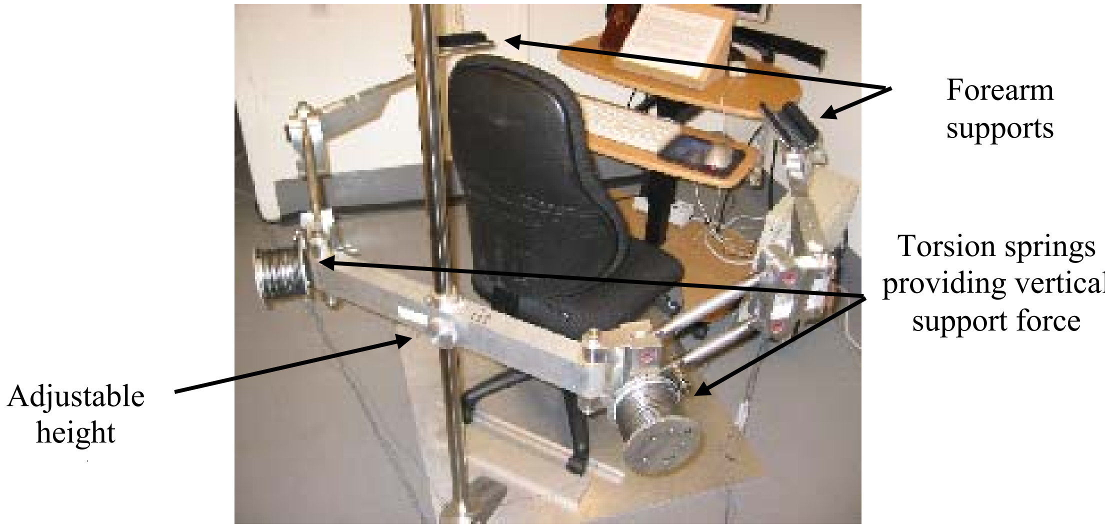


Figure 2.1.1: The Dynamic Forearm Support Device – Seated Configuration

2.2 Methods and Materials

2.2.1 Participants

Eleven healthy volunteers (5 females, 6 males) participated in the study. Ten of the subjects were right-handed. The subjects had a mean height of 68 inches (SD=3.6", range: 60"-74"), and a mean weight of 150 pounds (SD=25.4 lbs.). Participant ages ranged from 30 to "over 50" – the most accurate age our oldest subject was willing to provide. The sitting and standing elbow heights of subjects were 26.2 inches (SD=0.88"), and 45.25 inches (SD=2"), respectively. The participants were video taped during task performance and data collection. The study was approved by the institutional review board of LBNL, UC Berkeley and UC San Francisco.

2.2.2 Environment

The dynamic armrest was positioned in a small room with a workstation on one side of the arm support device, and a worktable on the other. In this way, the device could be rotated 180° to test both seated and standing tasks. The subject's chair and workstation heights were configured for each participant's anthropometry. The workstation height was set so that the keyboard key surface was ½" below seated elbow height. The standing worktable height was set to 9 inches below elbow height. The support device height was adjusted to accommodate the subject's standing or sitting elbow height.

The spring tension of the device was also set at this point. The spring tension of the dynamic armrest was adjusted to a level where the subjects reported that their arms were reasonably supported but were not being pushed up. Spring tension was the amount of support (vertical force) offered by the springs. The mean subject preferred spring tension was 2.2 pounds (SD = 0.64 lbs.), with a range of 1 to 3 pounds. Three subjects requested different spring settings for each arm.

2.2.3 Procedure

Subjects performed 10 different tasks (5 seated and 5 standing). The tasks were performed in a fixed order both with and without the arm support device, for a total of twenty test conditions. Within a task, the order of whether the task was performed first with or without the support device was determined at random using a random number generator. Therefore, the study design was a full-block, repeated-measures experiment.

Prior to data collection, participants practiced each task, with and without the support system, until they were comfortable performing the task. Data collection captured a one-minute EMG sample for each task, capturing many task cycles. Participants were not notified, however, when the data collection began or ended. Data collection began in the non-extended posture for dynamic tasks. After each task, users completed a short questionnaire asking them to rate forearm comfort, shoulder effort, and ease of completing the task with and without the device on a continuous scale rated from one (comfortable) to five (uncomfortable).

2.2.4 Task Descriptions

The tasks, in order, were: seated static posture, seated arm swinging, seated reaching, seated keyboard data entry, seated mousing, standing static posture, standing arm swinging, standing reaching, standing drilling simulation, and standing static extended posture. The seated and standing static posture tasks required participants to hold their upper arms at their side and their forearms parallel to the ground with their fingers extended comfortably. The standing static extended posture, was similar, but user maintained approximately 45 degrees of shoulder flexion. These tasks were intended to simulate static arm resting in preparation to performing an operation.

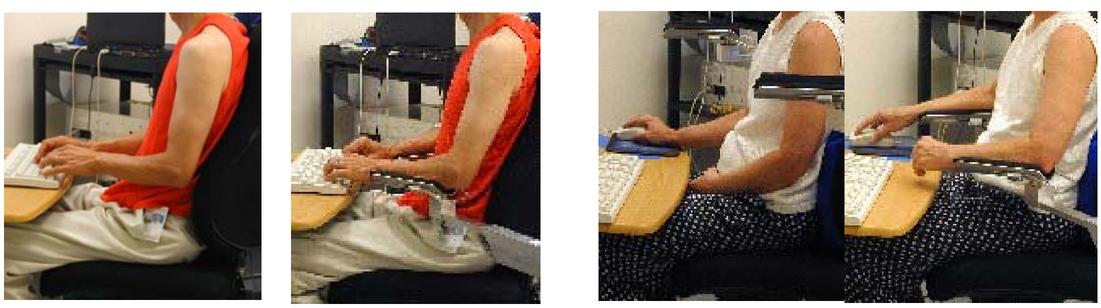
During the seated and standing arm sweeping tasks, participants were instructed to start in the same posture as the first 2 tasks, and rotate the forearms about the elbows while keeping the foreams parallel to the floor (internal/external shoulder rotation). These motions were from approximately 60 degrees of internal shoulder rotation to approximately 30 degrees of external shoulder rotation.

Static Posture Swinging Arm Motion Extremes

Figure 2.2.1: Seated Arm Motions

For the seated and standing dynamic arm reaching tasks, participants were instructed to keep their forearms in a plane parallel with the ground, and reach their arms forward to approximately forty five degrees of shoulder flexion. Wrists were held straight during this motion. Arm sweeping and reaching tasks were intended to represent moving the arms over a work surface while seated or standing.

The seated data entry task required participants to type a page from a book of fiction. Users self-positioned the chair-to-keyboard distance based on their personal level of comfort. The seated mousing task presented circular targets on the computer monitor at different distances, sizes, and directions around the screen (as recommended by the pointing standard in ISO 9241-9). The user was asked to click on the targets with the mouse as the targets appeared. Participants were encouraged to use their usual mousing technique. These tasks are shown in Figure 2.2.2.



Seated Typing Seated Mousing

Figure 2.2.2: Computer Input Tasks

The standing drilling simulation task (Figure 2.2.3) was selected to represent a common manufacturing or assembly operation. Participants used either a six or four pound drill (depending on participant's physical stature and their comfort with handling the larger drill), and were instructed to press one of five spring-loaded pins into a pegboard in sequence using only their dominant hand. Spring force was less than one pound, as springs were provided simply to return the pegs to the initial position. The pegboard distance from the shoulder was set to the location of the mid-palm when the shoulder was flexed to 45 degrees, and targets were positioned four inches above elbow height. The drill motor was not activated during this test. Subjects were instructed to perform dynamic tasks at a rate in time with a metronome set to 40 beats per minute.

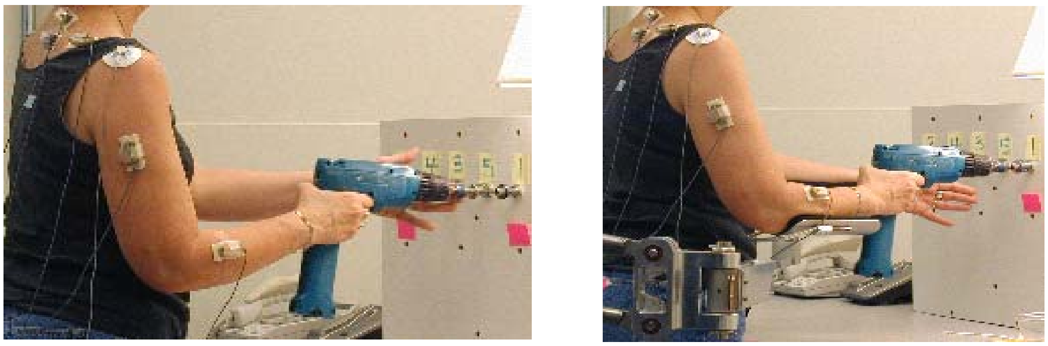


Figure 2.2.3: Standing Drilling Simulation

2.2.5 Electromyography (EMG)

Myoelectric activity was recorded using silver/silver chloride electrodes embedded in plastic with a preamplifier manufactured by Therapeutics Unlimited. These circular sensors have a contact diameter of 8 millimeters, and an inter-electrode distance of 20 centimeters. Skin was dry-shaved and cleaned with an alcohol wipe prior to sensor placement, and sensors were placed only on the dominant side. Conductive gel was used. EMG data was captured with a data acquisition card in a personal computer, sampling at 250 Hz. Data was smoothed at the amplifier using an Root Mean Square (RMS) filter with a 55 ms filtering window.

The electrodes were placed over the following muscle groups on the dominant extremity: 1) extensor carpi radialis, 2) lateral head of the triceps, 3) supraspinatus, 4) middle trapezius, and 5) upper trapezius.

These muscle groups were selected based on their high susceptibility to fatigue or injury, and the anticipated likelihood that their activity would be influenced by the support device.. Sensors were oriented in the direction of the muscle fibers and placed according to the recommendation of Delagi et al., 1981.

2.2.6 Maximum Voluntary Contraction (MVC)

To obtain reference electrical signals representing maximum voluntary exertion, three separate activities were performed to fully load the muscles of interest. These included wrist extension, wrist ulnar deviation and elbow extension, and shoulder abduction (Figure 2.2.4). Using a five second MVC sample time, the 95th percentile of the amplitude distribution for the activity was calculated for each trial, and the highest value of the three trials was used as the MVC value for that particular muscle.

a) Forearm Extensor MVC Activity b) Triceps MVC Activity c) Shoulder MVC

Figure 2.2.4: Isolated MVC Activities

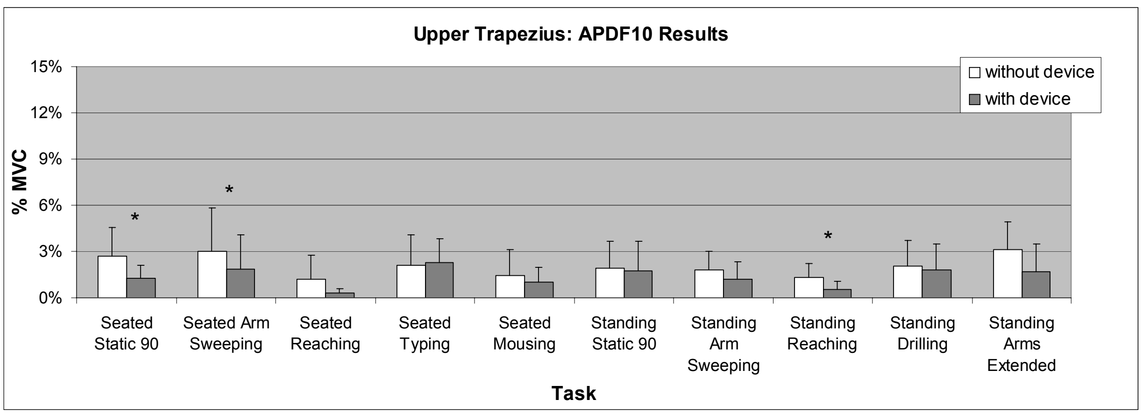
2.3 Analysis

All EMG signals were normalized to isometric Maximum Voluntary Contraction (MVC). Summary measures of EMG data were prepared for each subject, task, and support condition using the Amplitude Probability Distribution Function (APDF) values (Hagberg and Jonsson, 1975), at the 10% level. APDF values are amplitude signal percentiles, meaning that APDF 10% represents the 10^{th} percentile value of the amplitude signal. APDF 10% represents the static load of a given muscle throughout a task.

The effect of forearm support device on APDF values and subjective data was evaluated for each task using a two-tailed paired t-test. The null hypothesis was that the support device would have no effect on muscle activity, or subject preference. The p-value used for all tests was .05.

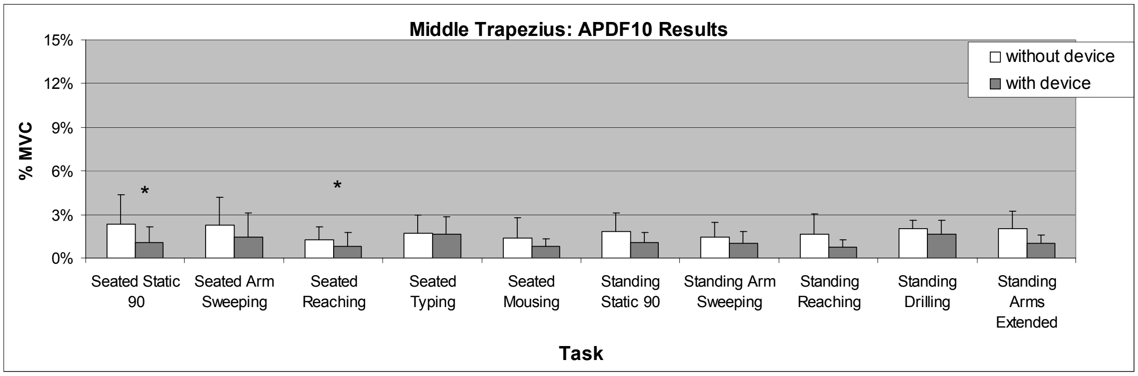
2.4 Results

Figures 2.4.1 through 2.4.8 show the results of each outcome measure by task differentiated by the "with device" and "without device" experimental conditions



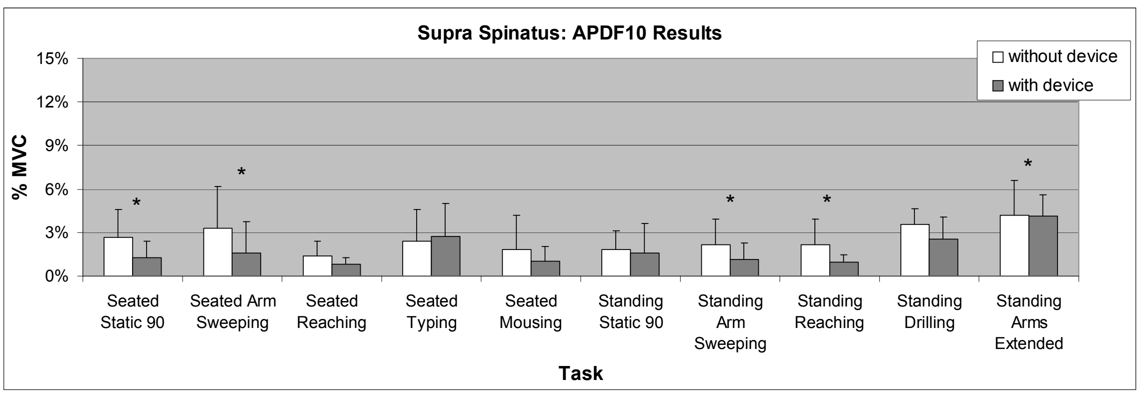
An asterisk (*) indicates a statistically significant difference at the 0.05 level.
Error bars represent one standard deviation. N=11 subjects for all tasks except 'standing arms extended' where N=8.

Figure 2.4.1: Upper Trapezius Static Load Results



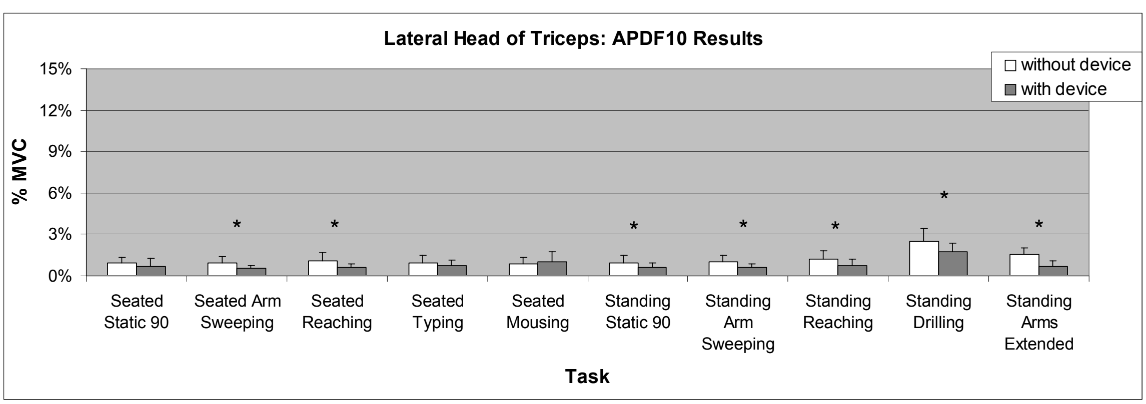
An asterisk (*) indicates a statistically significant difference at the 0.05 level.
Error bars represent one standard deviation. N=11 subjects for all tasks except ‘standing arms extended’ where N=8.

Figure 2.4.2: Middle Trapezius Static Load Results



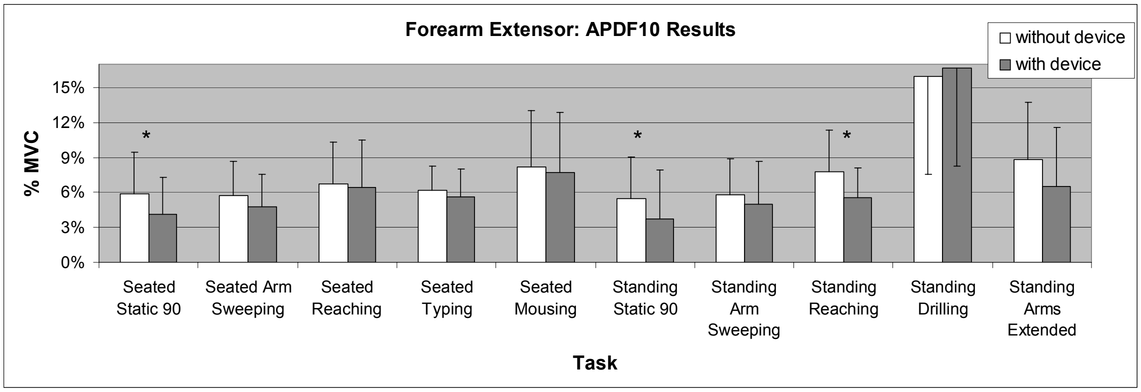
An asterisk (*) indicates a statistically significant difference at the 0.05 level.
Error bars represent one standard deviation. N=11 subjects for all tasks except ‘standing arms extended’ where N=8.

Figure 2.4.3: Suprspinatus Static Load Results



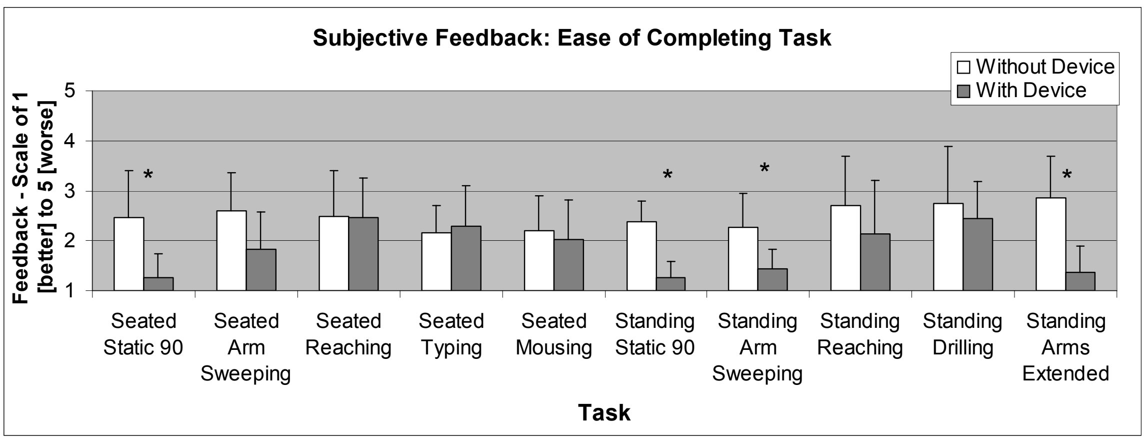
An asterisk (*) indicates a statistically significant difference at the 0.05 level.
Error bars represent one standard deviation. N=11 subjects for all tasks except ‘standing arms extended’ where N=8.

Figure 2.4.4: Triceps Lateral Head Static Load Results



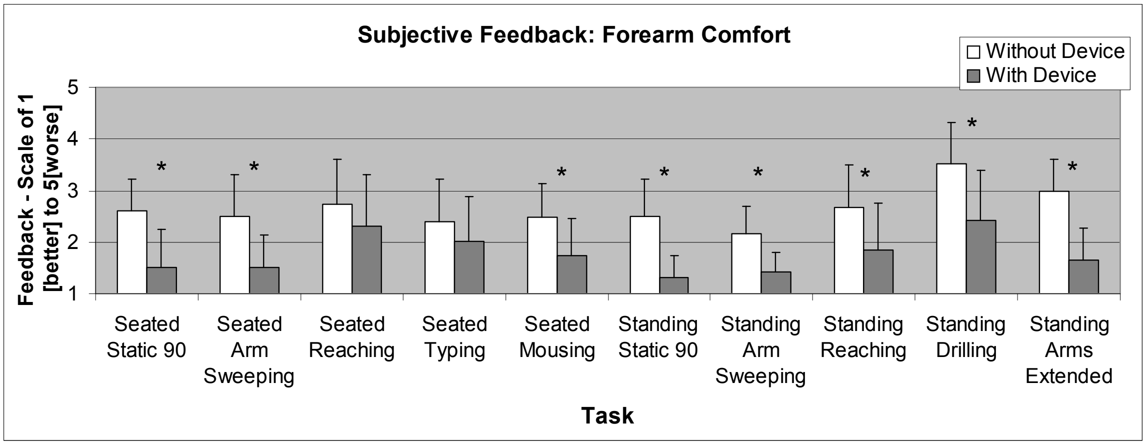
An asterisk (*) indicates a statistically significant difference at the 0.05 level.
Error bars represent one standard deviation. N=11 subjects for all tasks except ‘standing arms extended’ where N=8.

Figure 2.4.5: Forearm Extensor Static Load Results



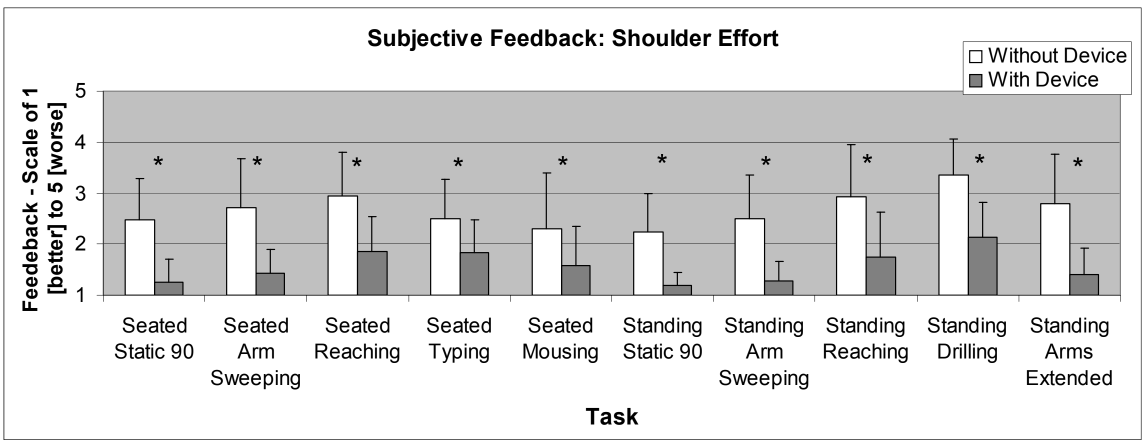
An asterisk (*) indicates a statistically significant difference at the 0.05 level.
Error bars represent one standard deviation. N=11 subjects for all tasks except ‘standing arms extended’ where N=8.

Figure 2.4.6: Subjective Feedback – ‘Ease of Task’ Results



An asterisk (*) indicates a statistically significant difference at the 0.05 level.
Error bars represent one standard deviation. N=11 subjects for all tasks except 'standing arms extended' where N=8.

Figure 2.4.7: Subjective Feedback – 'Forearm Comfort' Results



An asterisk (*) indicates a statistically significant difference at the 0.05 level.
Error bars represent one standard deviation. N=11 subjects for all tasks except 'standing arms extended' where N=8.

Figure 2.4.8: Subjective Feedback – 'Shoulder Effort' Results

2.5 Discussion

2.5.1 Muscle Group Activity

APDF 10% values for the upper and mid trapezius muscle are presented in Figures 2.4.1 and 2.4.2. Although all tasks, except typing, show trends towards static load reduction, only for seated reaching and seated static posture tasks were the reductions in static muscle activity for the middle trapezius statistically significant (Figure 7).

Previous studies have found similar statistically significant static load reductions of the trapezius under different loading conditions (Aaras et al., 1997, Feng at al., 1999, Visser et al., 2000).

The supraspinatus showed statistically significant static muscle load reduction for 5 tasks (Figure 2.4.3). For all tasks except for seated typing, a non-statistically significant beneficial trend in static load reduction was measured. The effects of suspended arm support (10-15N) on simulated assembly and welding tasks were previously studied (Jarvholm, et al., 1991). The output measures of this study were intramuscular pressure (IMP) and electromyography (EMG) measurements for the supraspinatus. Good correlation (r=.96) was found between intramuscular pressure and EMG readings, reinforcing the idea that EMG measurements represent a robust measure of muscle load. Statistically significant reductions of roughly 20% were found in both IMP and EMG readings for both tasks with arm support. These findings reinforce supraspinatus activity reduction findings with arm support from the present study.

The lateral head of the triceps showed a statistically significant reduction in static muscle load for seven of the ten tasks – the most of any muscle measured (Figure 2.4.4). Muscle loads in general were low in this muscle for all of the tested tasks.

As can be seen from Figure 2.4.5, extensor carpi radialus static loads were relatively high for all tasks. Many tasks required higher static load levels than the generally recommended five percent of MVC to reduce fatigue and risk of WMSD (Schuldt et al., 1986). The only tasks that showed a statistically significant reduction in static loading for the forearm extensors were the static postures (non-extended), and the standing reaching task. While other studies have measured and demonstrated high loads on the forearm extensors during various tasks, few have documented statistically significant load reductions for them (Feng et al., 1997 and 1999).

2.5.2 *Static Posture Discussion*

Seated static posture resting shows statistically significant reduction in static muscle activity with the armrest device on every muscle except the triceps. Reflecting this trend, the subjective feedback indicates statistically significant user preference for the "with device" condition for all three questions. Despite the similarities in task, the standing static posture task results are quite different. For standing static posture, statistically statistically significant EMG differences were only seen for the extensor carpii, and for the lateral tricep head. The different finding from the sitting tasks is understandable, since standing alters the loading and posture of the upper spine and shoulders in comparison to sitting.

2.5.3 *Arm Swinging Discussion*

The arm sweeping tasks required users to perform internal and external shoulder rotation. There was a very smooth rotary joint directly below the participant's elbows, so this was a low-friction, low-inertia motion for the device. Overall, muscle activity remained quite low throughout this task.

2.5.4 *Seated Arm Reaching Discussion*

In performing the arm reaching tasks, participants moved all of the device's linkages and joints. This means that these tasks brought into effect the full friction and inertia of the device. As can be seen from "ease of task" results, users felt that reaching was equivalently difficult with and without the device. Additionally, measured peak forces

(APDF95 level) were statistically significantly higher for the middle and upper trapezius with the device than without for the seated reaching task – the only task with any statistically significantly higher muscle activity with the device at any analyzed level. This information, as well as subjective feedback, indicates that a reduction of inertia and friction in the device is likely to make this task easier to perform.

2.5.5 Seated Keyboard Text Entry Discussion

The typing task showed no statistically significant static muscle load benefit from subjects using the arm support device. This result is puzzling considering the strongly positive results found for the seated arm posture task, which required a similar posture to typing. One likely explanation for this is that the workstation was set to a very comfortable position before testing began. This ergonomic alignment may have corrected much of the loading associated with keying at standard workstation. Therefore, results of this test may look dramatically different if the device were compared with a typical workstation arrangement, rather than an ergonomically adjusted one. Users subjectively indicated that shoulder effort was statistically significantly reduced when using the device. Previous studies have found strong evidence that forearm support reduces muscle loads for keying tasks (Feng et al., 1997, Aaras et al., 1997, Visser et al., 2000, Erdelyi et al., 1988). These studies bolster the subjective findings of this study, and indicate that the load reduction trends observed in this study would likely become statistically significant with more subjects.

2.5.6 Seated Mousing Discussion

Similar to the Seated Keyboard task, the armrest device demonstrated no statistically significant reduction in static muscle loading for the Seated Mousing task. However, in this case, the data shows a trend towards reducing the load for all muscles (except the Triceps Lateral Head), which might become statistically significant in a higher power study (e.g. more subjects). The results of previous studies (Aaras et al., 1997, Visser et al., 2000) lend credence to this idea, as those studies found statistically significant static load reduction in the trapezius for a mousing task performed with arm support. Note that this task required the Forearm Extensor Carpii to exert a static force of more than 7.5% of MVC (higher than the recommended cutoff value of 5% (Schuldt et al., 1986)). This finding indicates that mousing likely generates a long-term injury risk to the exensor carpi.

In addition to these findings, another important observation was made with respect to different subject behavior between the "with device" and "without device" conditions. All subjects whose mousing posture was explicitly examined planted their wrists during this task with no support device – resting their palms on the mouse pad. However, these same subjects (N=8) were observed to keep their wrists above the mousing surface while mousing with the support device. See Figure 2.2.2 for an example of this postural change. Contact pressure on the wrist and wrist extension have been linked with an increased risk for hand and wrist pain among computer users (Marcus et al., 2002). So, for the mousing task, the presence of the support device seems to offer potential advantages beyond the trends for reduced static muscle load.

2.5.7 Standing Drilling Simulation Discussion

Forearm Extensor activity was very high for this task (with and without forearm support), indicating that this task is likely to lead to fatigue over extended periods of time. Many participants reported feeling forearm fatigue after two minutes of performing this task. High forearm force was required to order to keep the drill pointed up during this task. To reduce this high force, support would be better offered at the tool itself (rather than at the forearm) in order to reduce the large moment about the wrist that is caused by the weight of the drill.

2.5.8 Subjective Feedback Discussion – Ease of Task, Forearm Comfort, and Shoulder Effort Rankings

Standing arm swinging is the only *dynamic* task that users found to be **easier to perform** to a statistically significant degree (Figure 2.4.6). Users felt that all of the static tasks were easier to perform with the arm support. This hints not only that arm support makes tasks easier to perform, but also that the additional inertia and friction of the current support device design may simultaneously increase the difficulty for dynamic tasks, balancing out the overall ease-of-use benefits.

The presence of the dynamic arm rest was found to statistically significantly improve **forearm comfort** for all of the measured tasks, except for the seated reaching and seated typing tasks (Figure 2.4.7). For those two tasks, a non-statistically significant forearm comfort improvement trend was noted.

Subjectively, users found **shoulder effort** to be statistically significantly reduced by the device for all tasks (Figure 2.4.8). Quantitatively, statistically significant reductions in shoulder static muscle load were found for six of ten tasks. Subjects may have felt reductions in other shoulder muscles that were not studied in this experiment, as tested muscles were selected based on their susceptibility to injury. Another study, for example, found the most dramatic muscle load reductions in the deltoid muscles with forearm support (Feng et al., 1997).

2.5.9 Subjective Feedback Discussion – Open-ended Feedback

Comments from study participants as well as experimental observations yielded some feedback about the design of the forearm support device.

1) Device inertia and static friction should be low in forearm-tracking support devices to improve usability, and reduce task-induced loads. Inertia and static friction increase the forces required to move the device, and therefore the forces required to perform a given task. Static postures are not much affected by inertia and friction, whereas dynamic tasks are more affected. Peak task forces are more affected by the presence of high inertia and friction than static loads.

2) Proper forearm coupling is important for tasks that require rapid motions, particularly in the presence of high support device inertia or friction. Otherwise, the support device may not properly track the user's forearms. Coupling is more difficult in the vertical direction, and there may often be a tradeoff between secure coupling and user comfort.

3) The forearm support length should be adjustable to accommodate smaller sized subjects.

These pieces of information are applicable to a broad range of dynamic support devices, and are therefore useful in the design of future forearm support devices.

	* indicates statistically significant benefit from device					
	Static Load EMG Findings			Subjective Findings		
N=11	Shoulder	Triceps	Forearm	Ease of Task	Shoulder Effort	Forearm Comfort
Sitting w/ Arms @ 90 degrees static	*		*	*	*	*
Sitting w/ Arms Sweeping	*	*			*	*
Sitting w/ Arms Reaching Forward	*	*			*	
Sitting and Typing					*	
Sitting and Targeting with Mouse					*	*
Standing w/ Arms @ 90 degrees static		*	*	*	*	*
Standing w/ Arms Sweeping/Swinging	*	*		*	*	*
Standing w/ Arms Reaching Forward	*	*	*		*	*
Standing and Drilling		*			*	*
Standing w/ Arms Extended static (N=8)	*	*		*	*	*

Table 2.5.1: Summary of Statistically Significant Findings

Table 2.5.1 summarizes the statistically significant findings of this study. For benefit magnitudes and trends, refer to the full results presentation in Figures 2.4.1 to 2.4.8.

2.6 Chapter Conclusions

Dynamic forearm support reduces task-related loads on the upper extremity for a variety of seated and standing tasks. Additionally, subjects noticed these changes. Subjective questionnaires indicated user preference for the device for most tasks along the metrics of "ease of use," "shoulder effort," and "forearm comfort."

Despite the fact that no statistically significant reductions in static muscle load were noted for computer input tasks, muscle load reduction trends were noted for many of the muscles associated with computer input. These trends towards reduced static loads are important, as it is likely that higher power tests will reveal statistically significant differences. Additionally, subjective measures revealed statistically significant user preference for performing the computer input tasks with forearm support. This was due to its perceived benefit for reducing shoulder effort, and improving forearm comfort. Finally, visual observation indicated that forearm support may provide benefits for working posture and wrist contact pressure during computer input – additional risk factors for Musculoskeletal Disorders.

Chapter 3: Design of a New Integrated Input Station - the Command Chair

3.1: Motivation: Anticipated Benefits of an Integrated Workstation

As mentioned in the introduction, there are several anticipated benefits to integrating bimanual computer input with forearm support in a computer workstation. In addition, integrating a collection of input devices into a single input station provides several benefits as well. This is because the hardware system can be considered as a whole system, rather than as a collection of individual devices designed by different people with different goals. In turn, this allows better control of body activities and postures, with the goal of providing user comfort over a full workday. With ergonomic considerations in mind, the goals of the new integrated workstation were to design a system capable of:

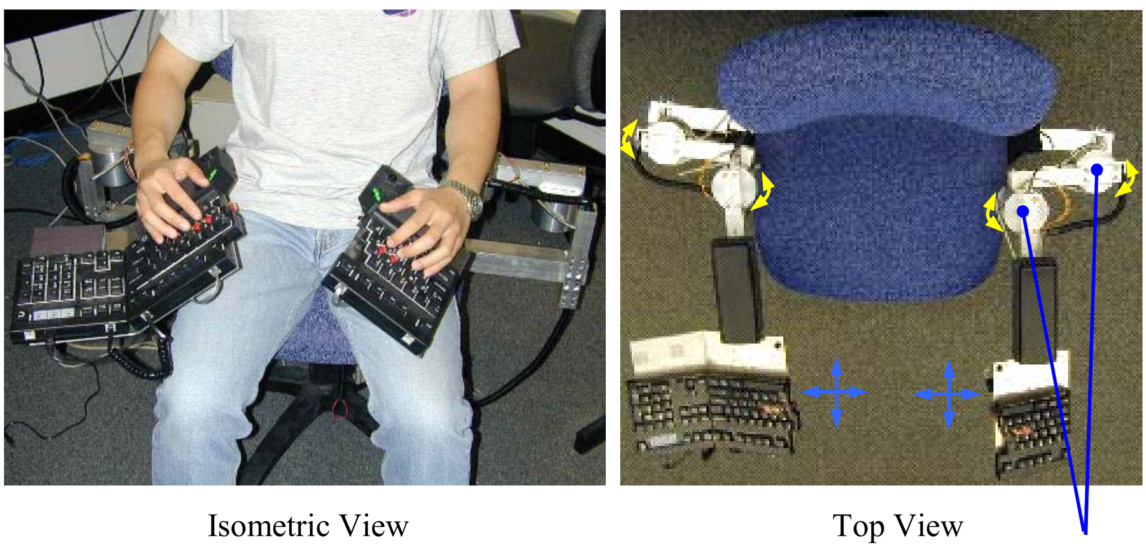
- Aligning the wrists into a neutral position.
- Supporting the lower arm to reduce static loading on the upper extremities.
- Allowing for more adjustability and flexibility in workstation configuration by eliminating the disconnect between a user's chair and working surface.
- Reducing the time required to switch between input devices.
- Splitting input motions between two arms, reducing the repetitions on a single limb.
- Removing input loads from small muscles and tendons, by shifting it to the larger groups in the upper arms.
- Providing multiple input devices within comfortable reach.
- Providing keyboard input in addition to multiple pointing devices.

3.2: The Command Chair Prototype

Prototyping has become a key step in the product realization process (Ulrich and Eppinger, 2000, Wright, 2001). It leads to a fuller understanding of the product's functions, the interactions between electrical and mechanical components (Lee et al., 2003) and the success (or failure) of user interfaces. One or more prototypes are especially needed during the design and construction of a totally new device that aims to solve many ergonomic and usability challenges. To create the new integrated workstation, called the "Command Chair," a series of prototypes were thus built, with different purposes and levels of functionality. These led to a series of "lessons learned" for the final device, and are presented in section 3.2.2. The final Command Chair is described in Section 3.3.

To achieve the goals stated in section 3.1, the Command Chair concept integrates an office chair, keyboard input, bimanual pointer input, and forearm support into a single system (see Figure 3.1.1). The Command Chair is a novel device that provides a two degree-of-freedom input for each arm. This device consists of two movable articulating armrests with a half-keyboard at the end of each linkage. Mouse buttons are integrated into the keyboards. The armatures are attached to an office chair, thereby allowing keyboard height to be adjusted relative to chair height. *The planar motion of the keyboard-halves is used as the pointer input into the computer.* Coupling the location of the pointer to the keyboard position obviates the need to switch between input devices and reduces homing time dramatically. By integrating the keyboard and pointer input into a single device, the Command Chair facilitates workstation adjustability and flexibility, and relieves the crowding of the ideal working space by providing a single device for users to work with.

In addition, the Command Chair addresses a problem specific to bimanual computer interfacing – the loss of keyboard input for command selection. Or, as Balakrishnan states in his paper addressing the same problem, “I’ve got two hands, but lost my hotkeys!” (Balakrishnan and Patel, 1998). This is because the use of two pointing devices simultaneously typically precludes the use of hotkeys, since both hands are on pointing devices, and neither on the keyboard. This can diminish the value of the bimanual system. The Command Chair provides both keyboard input and bimanual pointer input.

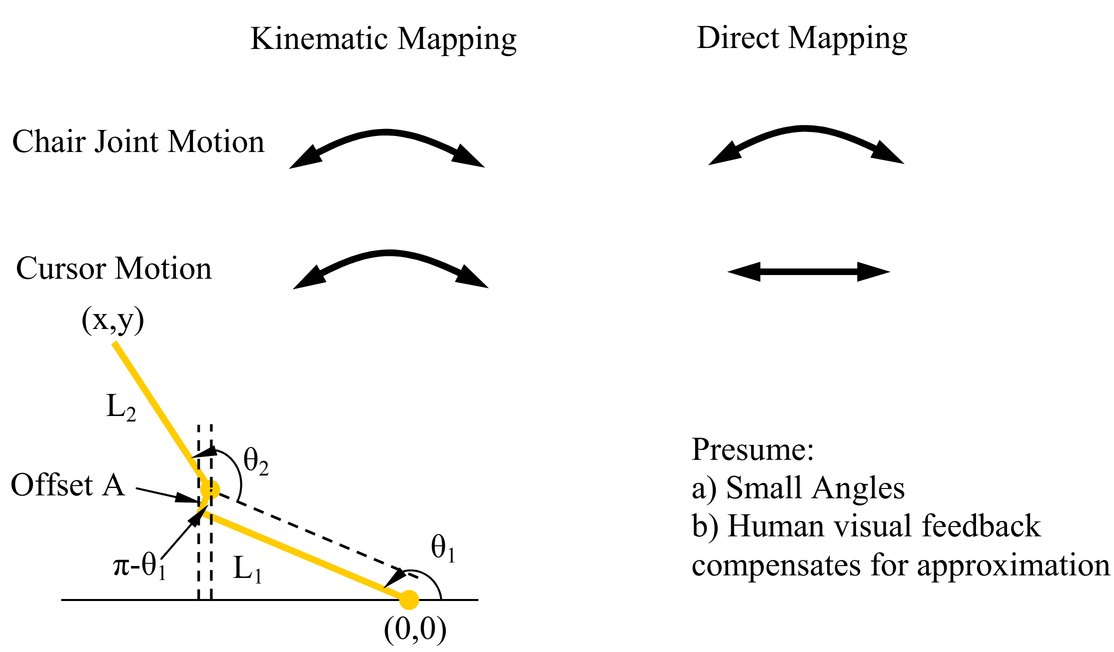


Isometric View   Top View

Figure 3.1.1: Command Chair Prototype

The first version of the Command Chair consists of four articulating rotary joints (two for each arm), coupled by connecting links. The joints contain optical encoders that sense the rotation of the joint, and thrust bearings to provide a smooth motion. Encoder signals are interpreted by a FPGA (Field Programmable Gate Array) board, which sends the rotary joint displacement information to a DSP (Digital Signal Processor) board. The DSP then calculates the position of the end of the movable armatures using one of two position mappings. The appropriate mouse signals are then calculated and sent to the computer via a standard PS/2 or serial interface.

There are two motion mappings of the Command Chair: *kinematic* and *direct* (Figure 3.1.2). The kinematic model represents the precise mathematical relation to calculate the position of the end of the armature based on the rotation of the joints. The direct mapping treats the angular displacement of the two joints directly as the horizontal and vertical translations of the pointer. Essentially, this mapping uses the small angle approximation for 'sine' and 'cosine' functions. In the direct mapping case, a rotation of the second joint will cause the output pointer motion to follow a straight path (rather than an arc).



$$X = L1*\cos(\theta_1)+L2*\cos(\theta_2+\theta_1-\pi)-A*\sin(\pi-\theta_1)$$
$$Y = L1*\sin(\theta_1)+L2*\sin(\theta_2+\theta_1-\pi)-A*\cos(\pi-\theta_1)$$

$$\Delta X = L_2*\Delta\theta_2$$
$$\Delta Y = L_1*\Delta\theta_1$$

Figure 3.1.2: Command Chair Prototype – Motion Mappings

The two mappings of the first Command Chair were included to test different electrical hardware implementations, and to explore humans' ability to accommodate approximations between physical input motions and virtual cursor motions. The kinematic mapping electrical hardware was much simpler to implement, and more electronically robust. An early study demonstrated that there was no significant difference in the performance of the two different mappings (Odell and Wright, 2003). Therefore, the kinematic mapping was more often used.

3.2.1: Ergonomic Aspects of the Command Chair

In addition to the ergonomic benefits inherent in the integration of the workstation components into a single system, several other workstation ergonomic concepts were culled from the literature and incorporated into the Command Chair. A recent epidemiological study linking workstation configuration to MSD risk was particularly useful (Marcus et al., 2002). This study provided information about proper interior elbow angle, elbow height relative to the keyboard, wrist position, and reemphasized the importance of forearm support. Other studies provided information about maintaining the wrist in a neutral position, and typing on a slight decline (Bach et al., 1997, Rempel et al., 1998, Hedge et al., 1999, Zecevic et al., 2000).

The Command Chair maintains a user's wrist in a neutral position in both deviation and extension (<10°). It still requires the user's wrists to maintain about 75° of pronation – necessary so that users can see the keys as they are typing. Once again, the integration of the system allows for the designer to carefully control these postures. Unlike a mouse, the Command Chair requires no wrist motion for pointer input – enabling wrist posture to remain constant during computer input. The placement of the forearm support relative to the keyboard is the key design factor for constraining the user's wrist posture to be neutral.

Contact pressure on the wrist or elbow is another risk factor for repetitive injury. This is because contact pressure on these areas can interrupt circulation and impair nerve function (Phalen 1966, Dahlin 1991, Rempel et al., 1999). Arm support on the Command Chair is only provided under the forearm, relieving contact stress from the elbows and wrists. There is no contact between the Command Chair and the user's wrists or elbows. Figure 3.1.3 summarizes these ergonomic concepts as they were incorporated into the Command Chair.

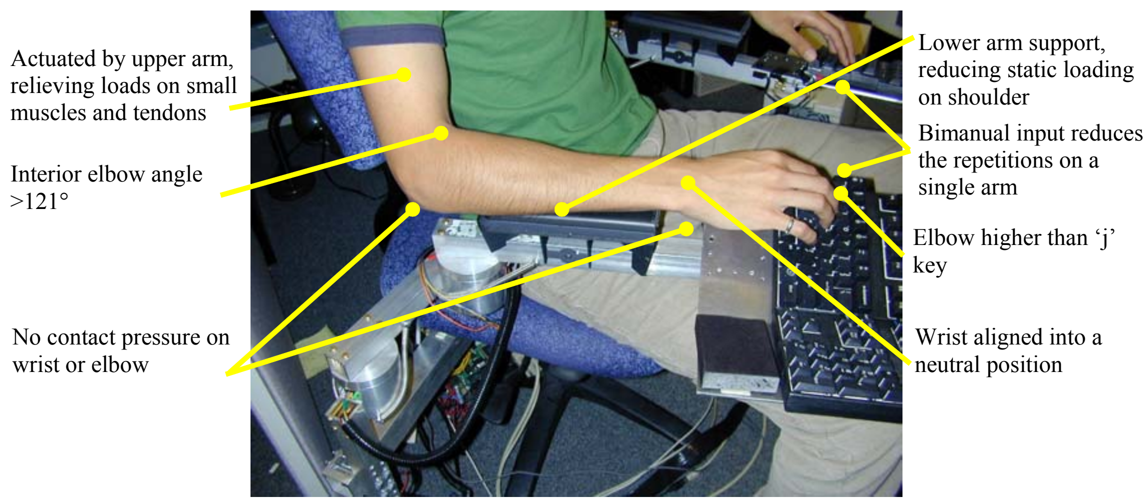


Figure 3.1.3: Command Chair Ergonomic Concepts

It is also important to note that the Command Chair is actuated by the upper arm and shoulder muscles. Upper arm actuation is not clearly a beneficial or detrimental design decision, and the community seems to be undecided on this issue. Many ergonomists, physical therapists, and ergonomic standards recommend removing input loads from small muscles and tendons in the lower arm, and shifting them to the larger groups in the upper arm (CSA-Z412-00). They believe that this reduces the risk of injury since these larger groups seem to be better able to withstand static loading. Others argue that there is no clear research backing this argument.

Studies on the 3M *Renaissance* mouse – a shoulder actuated pointing device - found significant reduction in subjective pain for long-term use (Aaras et al., 1999, Aaras et al., 2001). This study was more concerned with the postural changes caused by the new pointing device, rather than the musculature required to use it. But the observed benefits from the device are likely due to a variety of design factors, including both posture and actuation musculature. So, while the injury-risk benefits of pointing devices actuated by the upper arm and shoulder remain unclear, this study does provide some support for the argument that devices actuated by the upper arm can be more comfortable than traditional devices.

Similarly, the effect on accuracy and pointing speed for devices actuated by the upper arm relative to devices actuated by the lower arm is also unclear. The traditional wisdom is that the proximal muscle groups are best for gross movements with low accuracy, while the distal muscle groups are best for fine movements requiring higher accuracy (Rosenbaum et al., 1991). The 3M *Renaissance* mouse was found to be about ten percent slower than a conventional mouse (Aaras et al., 2001), but it is unclear if this is due to the change in musculature, or other changes (form factor, etc.).

Studies have been performed to isolate different segments of the arm and quantify their pointing performance. However, the studies have found conflicting results. Some studies have verified the traditional wisdom that proximal muscle groups demonstrated diminished pointing performance relative to the distal groups (Hammerton and Tickner, 1966, Langolf et al., 1976). However, a more modern study addressing some of the experimental design flaws of the previous studies found similar pointing performance for different arm segments, with the lowest pointing performance found in the fingers (Balakrishnan and MacKenzie, 1997). So, this issue remains somewhat unclear, as well.

But, despite these uncertainties, the Command Chair was designed to be actuated with the upper arm and shoulders. The potential reduction in performance of pointing speed and accuracy were seen as acceptable to achieve the anticipated ergonomic benefits. Even if the end result were reduced pointing performance, the device would still be very useful – particularly to people suffering from wrist injuries who are no longer able to use conventional wrist actuated pointing devices.

3.2.2: Lesson Learned from the Command Chair Prototype

The prototype of the Command Chair had several shortcomings which inhibited its performance. These shortcomings were noted in order to correct them in the final Command Chair. First, there were several mechanical issues that affected the pointing performance of the device. The most severe of these issues was the fact that as the joints rotated to provide pointer motion, the effective moment arm about the joints changed. This meant that the device required different forces to actuate in different positions – resulting in a non-uniform and non-intuitive motion. Next, the device required spring centering to keep the armatures in position. If the armatures were not precisely level with the ground, or centered with springs, gravity would pull them resulting in unintended motions and static loads on the user to resist this force. However, the presence of springs meant that the armatures required more force to position (especially near the extremes). The final major mechanical shortcoming of the first version of the Command Chair was that the keyboards were too massive – adding a great amount of inertia to the system. As mentioned in the previous chapter, this problem is similar to some of the problems inherent in the design of the LBNL armature. (Note that these devices were designed in parallel by two separate design teams). Once again, this inertia made maneuvering the armature more difficult, particularly for fine motions. The asymmetry of the keyboard also played a factor in this, as the primary pointer (controlled by the right hand) had the most inertia due to the presence of the numeric keypad on the right side of the keyboard.

In addition to mechanical problems, electrical problems also plagued the first iteration of the Command Chair — making the device fragile and user unfriendly. The main problem was the wiring required for the boards, sensors, and computer to communicate. In addition to being difficult to assemble, the wiring made debugging extremely difficult, as the whole system had to be examined anytime something stopped working. Worse, the wires were quite fragile, and could be pulled out of the breadboards quite easily - making the system quite delicate. Finally, the electrical design required two hardware circuit boards to communicate with the computer (in addition to the mouse boards). These boards had to be programmed prior to each use, meaning that the use of the system required significant time and knowledge to initialize.

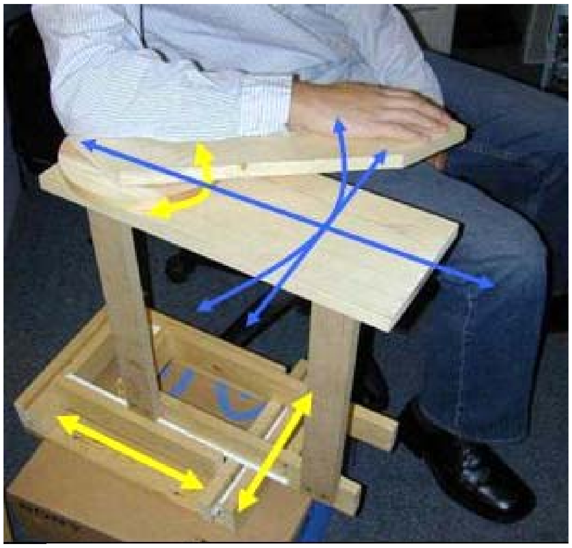
A study exploring the quantitative performance of the first version of the Command Chair was performed (Odell and Wright, 2003). A one-dimensional Fitts' tapping test was undertaken comparing the two mappings of the Command Chair with a conventional workstation using a mouse. Fitts' tests are described in Chapter 4. In addition, subjective feedback was collected using post-test questionnaires (provided in the Appendix). The results of the study found that the Command Chair performed roughly 50% slower than a conventional mouse for dominant-hand pointing, and that both mappings performed similarly. Additionally, users subjectively felt the device was difficult to point with (for the reasons mentioned above), supporting the quantitative data. On the positive side, users did find the chair to be comfortable to use, and easy to learn. Additionally, they also noted a reduction in wrist fatigue, and a corresponding increase in shoulder fatigue. These findings are encouraging, because they validate the design intent of the device. Overall, this study re-emphasized many of the shortcomings noted in this section, and pointed to the need to improve the device.

3.3: The Command Chair

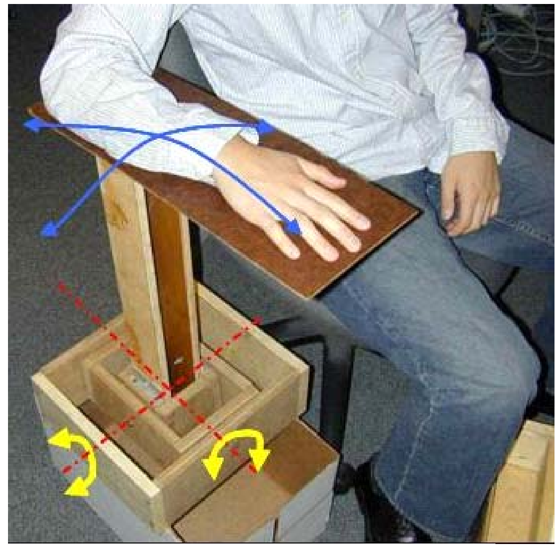
3.3.1: Command Chair Concept Generation and Selection

The final version of the Command Chair was intended to address the shortcomings of the original device, as well as incorporate the benefits and avoiding the shortcomings of the LBNL Ergo arm. To do this, the concept of the Command Chair was completely revisited. This is because a new approach was necessary to avoid to problems inherent in the joint/linkage approach (specifically the variable moment arms of the system). Many possible concepts were generated to address this specific problem, and four concepts were selected as promising enough to build a rough prototype out of wood. Figure 3.3.1 shows these prototypes. Light arrows represent the modes of motion of the mechanisms. Dark arrows show the resulting modes of motion available to the user's arm.

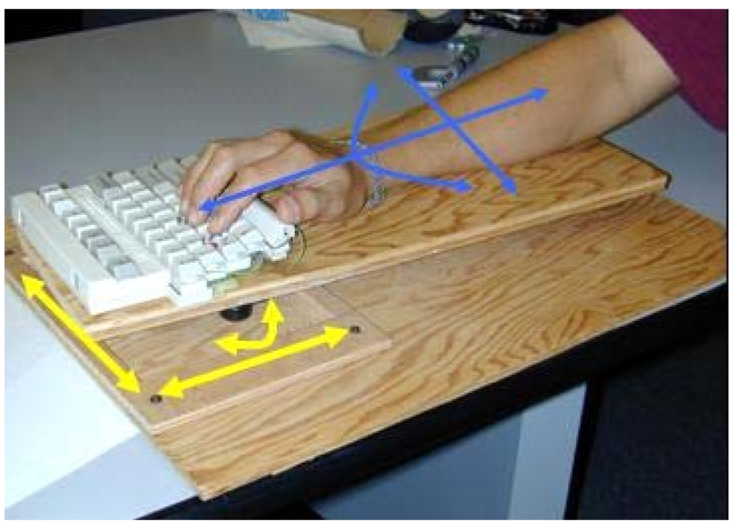
The linear slide concept used two sets of slides positioned orthogonally to each other to provide linear translation in the horizontal and vertical directions. However, this method did not provide for a natural motion, since the hand moves naturally in an arc about the elbow, rather than in pure translation. So, the second concept (linear/rotary) maintained a linear slide for the vertical direction, but replaced the horizontal slide with a rotary joint about the elbow – combining the best of the rotary linkage concept from the first version of the Command Chair with the linear slide concept. Sensors were envisioned as linear and rotary optical encoders.



Linear Slide/Rotary



Gimbal



Caster Cart

Figure 3.3.1: Command Chair mk.II Concepts

The Gimbal concept provided a very smooth and natural arm motion, allowing the user to move the armature over a spherical surface. It did this by incorporating a gimbal (a frame consisting of two rotary joints mounted at right angles to each other) in the base of the armature, with a long armature extending to the support platform. The long armature was necessary to provide motion over a large sphere (motion that is roughly planar). The motion was very smooth because the long armature also provides a long moment arm to overcome any friction in the joints. Sensors were to be rotary encoders at the joints. But, sensors would have required very high resolution, since computer display resolution is high and the armatures travels through very small angles to provide the forearm motion necessary to actuate the pointer.

Finally, the Caster Cart concept worked by providing ball trasfers between two horizontal planes. This approach provided full planar freedom of motion (horizontal and vertical translation, as well as rotation), and a smooth motion. In this case, sensors would have been similar to a traditional optical mouse.

In order to evaluate the overall strengths and weaknesses of these concepts, and point to a single concept to pursue, a concept selection matrix (Ulrich and Eppinger, 2000) was generated (Table 3.3.1). This approach works by listing the relevant selection criteria on the left side of the matrix. Weightings are then assigned to each of these criteria, based on their importance to the final performance of the device. Each concept is then rated relative to the first version of the Command Chair. A score of one means much worse performance than the first Command Chair. A score of three means equivalent performance to the first Command Chair. A score of five means much better performance than the first Command Chair. In this case, scores were given based on the opinions of two researchers. The scores are then multiplied by the weightings, and the final scores are all added together. The concept that best meets the selection criteria is the one with the highest resulting score total. The Caster Cart concept came out the heavy favorite due to its smooth motion, ease of pointing, low inertia, and ease of manufacturing. Therefore, this concept was selected for the implementation of the next generation of Command Chair.

			Gimble		Linear Slide		Linear/Rotary		Caster Cart	
	Criteria	**Weight**	Rating	Score	Rating	Score	Rating	Score	Rating	Score
Manuf	Few Parts	7.50%	1	0.075	2	0.15	3	0.225	4	0.3
	Easy to Assemble	7.50%	1	0.075	2	0.15	3	0.225	4	0.3
	Part Cost	5.00%	3	0.15	3	0.15	2	0.1	5	0.25
Perform	smooth motion	15.00%	5	0.75	2	0.3	3	0.45	4	0.6
	uniform motion	5.00%	4	0.2	4	0.2	3	0.15	5	0.25
	centering mechanism	2.50%	5	0.125	3	0.075	2	0.05	2	0.05
	low inertia	10.00%	2	0.2	4	0.4	3	0.3	5	0.5
	low power consumption	2.50%	3	0.075	3	0.075	3	0.075	2	0.05
	dirt/damage resistant	5.00%	4	0.2	2	0.1	3	0.15	4	0.2
User	Visually exciting	5.00%	4	0.2	3	0.15	3	0.15	4	0.2
	comfortable motions	15.00%	5	0.75	3	0.45	4	0.6	5	0.75
	precise pointing	10.00%	3	0.3	4	0.4	2	0.2	5	0.5
	Adjustable	5.00%	2	0.1	3	0.15	3	0.15	4	0.2
	size	5.00%	1	0.05	3	0.15	3	0.15	4	0.2
Total		100.00%		3.250		2.900		2.975		4.350

Relative to Command Chair v1   1 = much worse   3 = same as   5 = much better

Table 3.3.1: Command Chair mk.II Concept Selection Matrix

3.3.2: Command Chair Implementation

Once the approach was selected via the concept selection matrix, the specific components and final design of the Command Chair were specified. The primary components of the system were the system chair, the caster cart system (including the motion sensors), armrests, and keyboard-halves. The *Aeron* chair was selected for the system for its comfort, aesthetics, and, most importantly its armrest support bracket. This bracket allows for simple mounting of armrest systems via two bolts, and provides armrest height adjustment built directly onto the chair. Height adjustment is somewhat difficult to design, so having it provided from base components greatly simplified the design of the Command Chair.

The main components of the caster cart system were the ball transfers, the motions stops, and the motion sensors. Nylon ball transfers one inch in diameter were selected to provide a smooth motion and low noise (McMaster part number 5674k47). An optical sensor from an existing optical mouse (a Logitech MouseMan® Traveler™) was selected for motion sensing. This greatly simplified the design of the electrical system, because this system included not only the motion sensor, but also the computer interface in both USB and PS/2 formats. This meant that no custom electrical hardware or programming was necessary in this system – contributing to greatly improved system robustness.

Initially, wireless sensor boards were used for the system. However, these required frequent battery changes or recharges. Also, the aluminum plates of the system interfered with the transmission range of the boards. Therefore, the receivers had to be mounted close to the mouse boards. The net effect of all of this was that each mouse board wound up requiring two wires going to the Command Chair – one for charging, and one for receiving. To remedy this silly problem, conventional high-quality wired optical mice replaced the wireless boards in the final implementation. To reduce the number of wires going to the computer, a USB hub was placed on the base of the chair.

The stops for the system required a little more thought, due to the small space constraints, the need for low weight, and the desire to maintain translation and rotation in the motion of the cart. The traditional method of stopping the device by providing an external enclosure from one of the plates around the opposite plate would have resulted in a device double the size of the required range of motion. (The range of motion for the Command Chair is roughly 3.25” vertical by 4.25” horizontal). This size would be much too large, too heavy, and would have resulted in the device hitting the user’s knees during operation. After brainstorming and prototyping several approaches, a slot and pin stop style was adopted. For this, two sets of orthogonal slots were cut into the plates – vertical slots in the top plate, and horizontal slots in the bottom. Delrin pins were then machined and set into these slots with a small amount of tension to prevent the top plate from lifting off of the bottom plate. The pins were able to slide smoothly through the slots providing translation equal to the slot lengths – stopping at the termination of the slot. Rotary travel was set by the width of the horizontal slots in the bottom plate, and the distance between the two sets of slots. This system effectively limited the travel of top plate, without adding excessive sliding friction.

As previously stated, armrests were provided under the forearm and pad of the palm – relieving contact pressure from the wrist and elbow. After trying a variety of configurations, simple flat gel pads (built from Fellowes® gel wrist rests and American Covers Cybergel Add-a-Pads®) were used to provide arm support and interface with the user's arms. The friction between these pads and the user's arms provided the input force to position the pointing device.

The final component of the system was the keyboards. Keyboard selection was difficult. The ideal keyboard was considered to be a light, symmetrical, completely split keyboard that could be easily be modified to accept additional mouse buttons in the interstices between the home keys under the index and forefingers (Figure 3.3.4). The switches selected for the mouse buttons were E-switch® #TL1100FF-160Q switches. Unfortunately, no wireless keyboards are currently available in a split configuration (making a completely wireless Command Chair currently extremely difficult to prototype). Initially, *Goldtouch*™ keyboards were used (Figure 3.3.2). These keyboards were fairly simple to manually split, and provided an integrated number keypad, which made them symmetrical. A custom wire harness was made to allow the keyboards to be widely split, and span the distance between the chair armatures. This harness was encased with flexible PVC conduit.

Figure 3.3.2: The Command Chair – heavy keyboards

Ultimately, these keyboards were abandoned due to their high weight. They were ruggedly built – incorporating heavy metal parts. Additionally, the thick wire harness added a lot of extra weight to the system, as well as some rigidity. The back of the keyboard did not provide for simple mounting. So, velcro was used to secure the keyboards. However, this mounting method was too compliant, making typing difficult and resulting in a poor feel for the system. For these reasons, the *Goldtouch*™ keyboards were replaced with very lightweight membrane keyboards. These keyboards were one-third the weight of the *Goldtouch*™ keyboards, but do not provide good tactile feedback during typing – reducing typing performance. So, in this case, typing speed and feel were traded for improved pointing performance through reduced system inertia. This tradeoff would not be necessary in full production of the Command Chair, since more advanced manufacturing techniques would be available.

Since these membrane keyboards are complete keyboards, a full keyboard was used to make the half-keyboard for each side. Roughly half of the keys were removed from each full keyboard to generate a half-keyboard, and the printed mylar sheet was folded underneath to maintain electrical connectivity. The two completely separate half-keyboards were then individually plugged into a USB hub mounted on the base of the chair.

Figure 3.3.3: The Command Chair– membrane keyboards

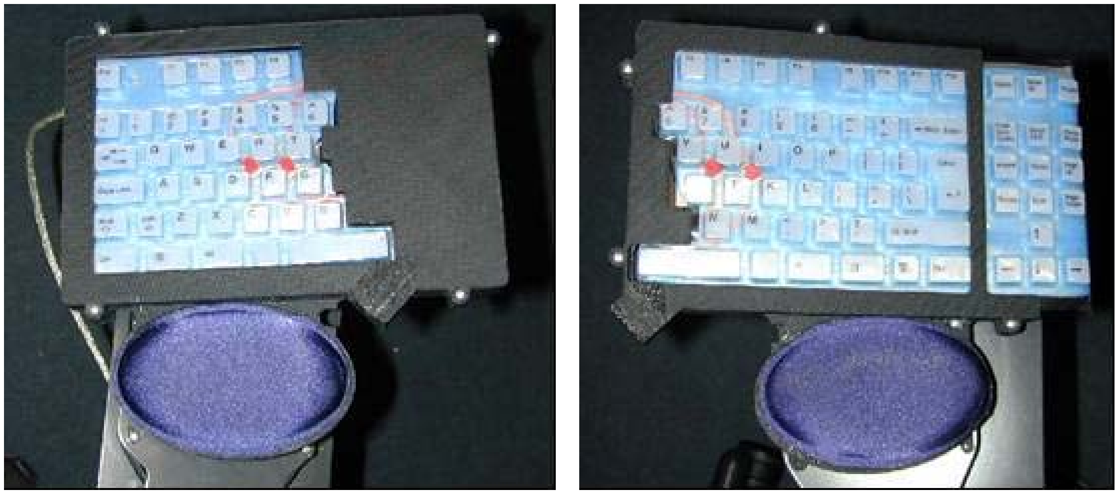


Figure 3.3.4: Command Chair Keyboards with Embedded Mouse Buttons

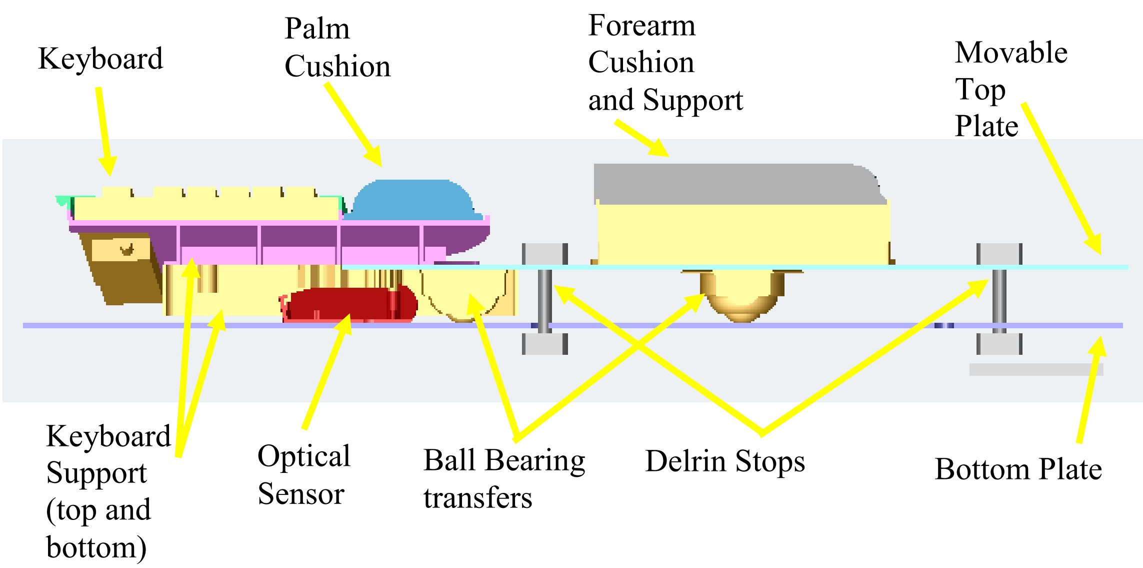


Figure 3.3.5: Section View of the Command Chair Solid Model (Right Side)

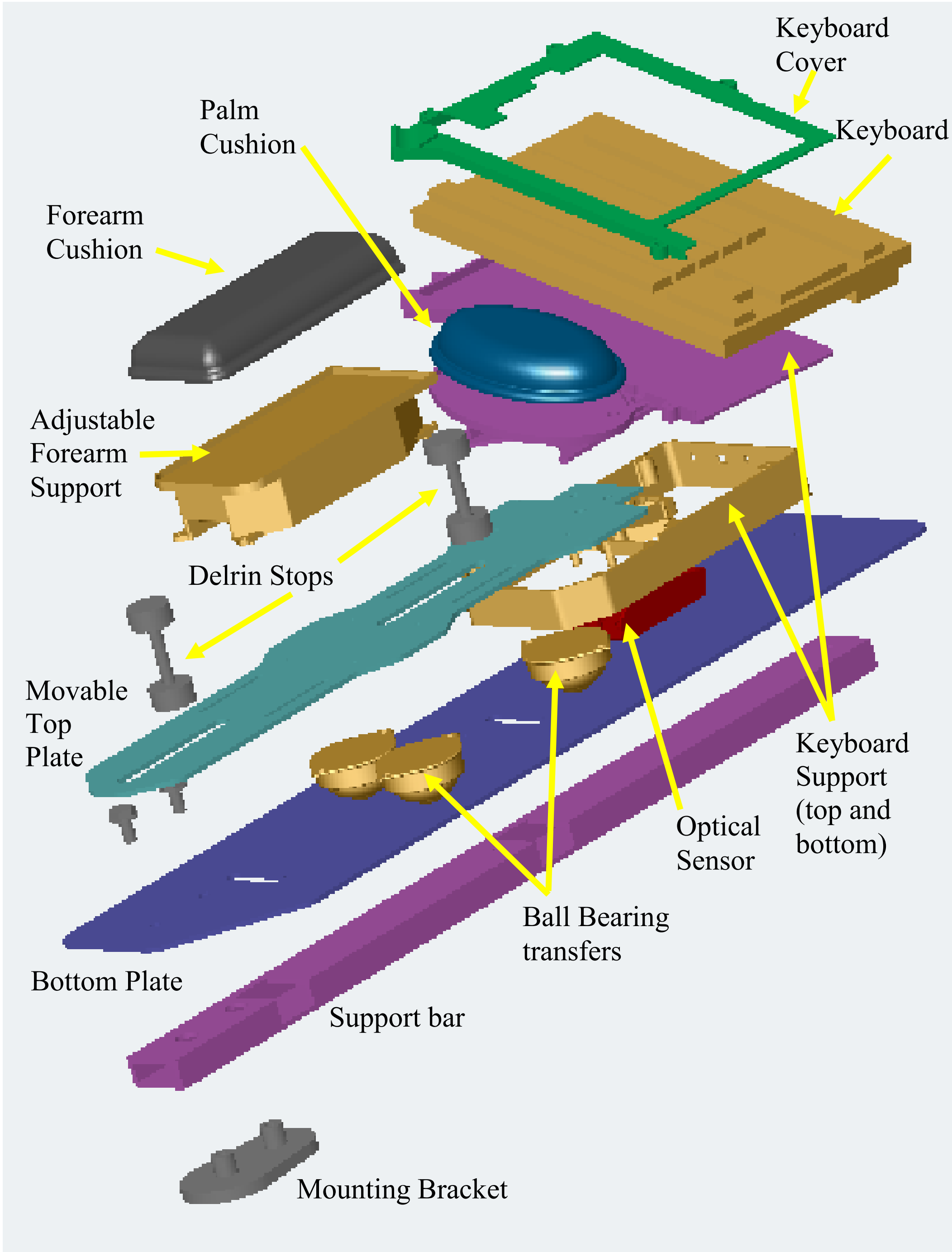


Figure 3.3.6: Exploded View of the Command Chair Solid Model (Right Side)

Chapter 4: Evaluation of the Command Chair

4.1: Evaluative Techniques for Computer Input Device Performance

As described in the previous chapter, the Command Chair was designed with the goals of making computer input more efficient, intuitive, and comfortable. This chapter will discuss some techniques for quantifying these performance characteristics, and present a study showing how these techniques were applied to the Command Chair. Results from these experiments will then be presented and discussed.

4.1.1 Measuring Efficiency - Fitts' Law and Workstation Throughput

The most commonly used metrics to measure input efficiency are speed and accuracy. Many tasks and performance measures exist to measure this sort of performance. These include dragging tasks (MacKenzie et al., 1991), steering tasks (Accot and Zhai, 1991), as well as drawing tasks, free-hand input tasks, and grasp-and-park tasks. But, the most commonly used method to determine the pointing speed and accuracy of a pointing device is to perform a Fitts' tapping test.

The Fitts' tapping test requires study participants to tap targets of varying size and distance from a home position (Figure 4.1.1), while measuring the time it takes them to tap those targets, and the accuracy of the taps. This data is then used to calculate the Fitts' predictive performance constants of the pointing device for that task. Fitt's law (Fitts, 1954) was developed to predict the time it takes a human to tap between two targets as a function of the distance between the targets and the size of the targets. Fitts' law has been shown to have a very high correlation with experimental data, and is robust to a variety of conditions (MacKenzie, 1992). For these reasons, it is very widely used.

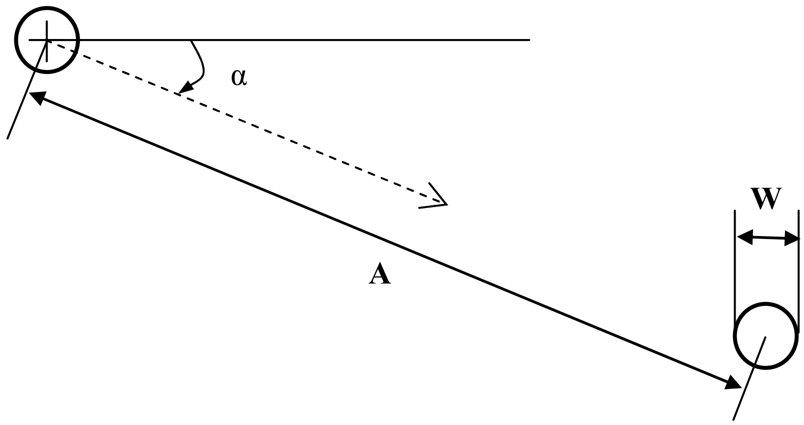


Figure 4.1.1: 2D Fitts' Tapping Task

A standard Fitts' testing software package, the Generalized Fitts' Law Model Builder (GFLMB) has been developed at the University of Guelph in Canada to assist researches in performing computer based Fitts' testing (Soukoreff and MacKenzie, 1995). Further, a standard for performing Fitts' tests for computer pointing devices is under development by the International Standards Organization (ISO 9241-9, 2000). The Shannon formulation is currently considered to be the most accurate form of Fitts' law, as it takes into account the nonlinearity observed for mean pointing times of small distances/large target size conditions, and prevents the possibility of negative prediction times.

The Shannon formulation of Fitts' law takes the form:

$$MT = a + b\log_2\left(\frac{A}{W_e} + 1\right)$$

Where:

MT = mean time to complete task

a, b = Fitts' constants

A = distance between centers of targets

W = target width

W_e = effective target width (used to account for the accuracy)

Also, the literature defines the additional terms below:

α = the angle between targets

ID = Index of Difficulty = $\log_2(A/W_e + 1)$

IP = Index of Performance = 1/b

Throughput = ID/MT (bits/sec.)

The Index of Difficulty is used to compare the relative difficulty of different pointing tasks (based on target size and distance). A higher Index of Difficulty indicates a more difficult (and therefore more time consuming) task. The Index of Performance is used to compare the performance of different pointing devices for similar trial conditions (higher IP indicates a faster device).

Similar to the Index of Performance, the concept of "throughput" allows for simple performance comparisons between devices, and is therefore the main factor to consider when evaluating devices. Throughput is similar to the Index of Performance, but assumes that the time constant intercept (the Fitts' constant "a") is zero. This assumption reduces the accuracy of time predictions made using throughput, but makes for very simple and meaningful performance comparisons between input devices. Throughput and Index of Performance comparisons take into consideration both the speed and accuracy of a pointing device by making use of the concept of "effective target width."

The effective target width is a statistical construction to account for the fact that some people tend to take more time and care during pointing in order to point more accurately than others. These people tend to get a very good grouping of hits right at the center of the target, but at the expense of slower pointing time. Because of this, the "effective" target width that those people use is actually much smaller than the presented target. To an extent, the effective target width varies between every user, as everyone has their own ideas regarding the acceptable tradeoff between speed and accuracy.

To evaluate the accuracy level of the user, the grouping of taps about the target center is assessed by calculating the standard deviation of the distribution of hits about the center of the target. The effective width is defined as the width within which ninety six percent of the measured taps fall — yielding a fixed error rate of four percent. Using this definition, the effective width is equal to 4.133 times the standard deviation of tap distance about the target center. This normalizes the effective target width to the same accuracy level for each subject (four percent). Note that the *effective* target width is calculated *after* the testing is complete, whereas target width is determined *before* testing and refers to the presented target size.

Throughput is determined experimentally, along with Fitts' constants "a" and "b". Note that all of these measures are task specific - meaning that predictive results do not extend beyond the scope of the experiment. However, the relative difference between two device's throughput values give a good idea of which device is faster in typical use. Therefore, Fitts' testing is still very useful for comparing pointing performance between different pointing devices, even for general cases.

Of course, one limitation of Fitts' law is that it is only applicable to testing the efficiency of *pointing* devices. To consider the efficiency of a full workstation, other metrics must also be considered as well. Tests have been performed to evaluate homing time — the time it takes to switch between input devices (Douglas and Mithal, 1994).

Additionally, typing speed tests are very common. However, testing for full workstation throughput, including pointing, typing, and homing has been very uncommon (McLoone et al., 2003, being one exception). Their experiment extended a standard Fitts' law test by popping up a text box to type at the completion of each pointing trial.

Since the Command Chair was designed as an integrated input station, other performance characteristics beyond pointing are necessary to document the efficiency of the full system. For this reason, a new test was developed which incorporated pointing, homing, and typing operations. This test was designed to simulate data entry in a spreadsheet or database application.

The new test, developed in this thesis research, presents a screen that is divided into rows and columns (Figure 4.1.2). The user points to the centermost cell (highlighted in black) to begin the test. This homes the cursor so that each trial begins with the cursor in a known position. Once the user clicks on the homing cell, one of the cells on the screen is highlighted with a specific color. The user must then point to and click on the highlighted cell, move the hand from the pointing device to the keyboard, and type the name of the color into the cell. Hitting the "Enter" key completes the typing portion of the test. The user then moves their hand from the keyboard back to the pointing device, and the cursor is then returned to the homing cell.

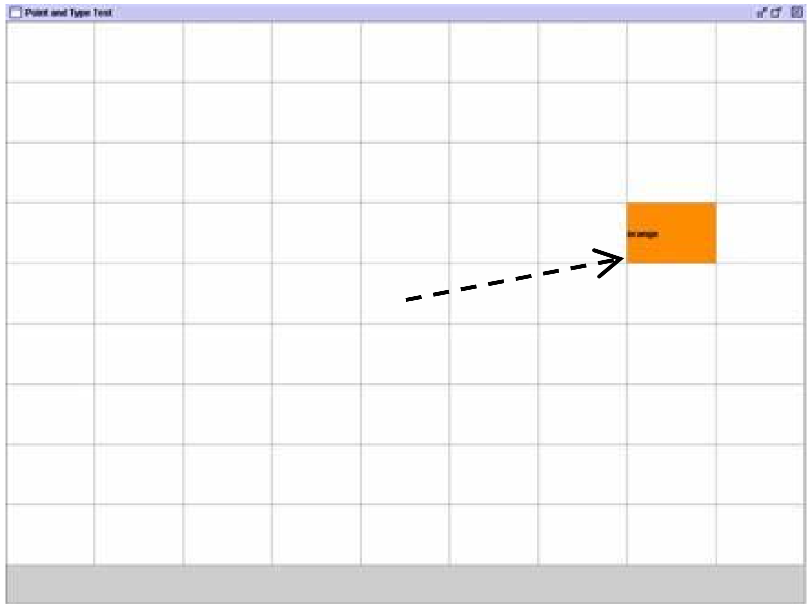


Figure 4.1.2: Workstation Throughput Test Task

The test software captures the times required for each portion of this test: point to highlighted cell, home to keyboard, type color name, home to pointing device, point to home cell. In addition, the software captures any pointing or typing errors.

For typing, the highlight color names were all selected to be six letters in length, and use a combination of letters typed by both the left and right hands. Examples include "purple" and "orange."

This testing approach has many strengths to recommend it. First and foremost, it provides a task that more completely quantifies workstation throughput than traditional methods. Also, it simulates commonly used applications (spreadsheets and databases) — meaning that the results of this test are likely to yield results that extend beyond the test environment. Finally, because it is similar to common applications, it is very easy to quickly understand the test sequence of actions. The primary limitation of this testing approach is that it allows for only one target size in this implementation (the size of all cells are equal).

4.1.2 Measuring Intuitive Input – Subjective, Learning

By stringing several small Fitts' tapping tests back-to-back, user performance can be tracked over time. These subtests are called "blocks" of the larger overall test. Improvements over time are typically due to learning and increased familiarity. Of course, boredom and fatigue can also potentially act to impair performance over time.

It has been shown that learning effects tend to follow an exponential improvement curve (DeJong, 1958). So, one way to report the magnitude of learning effects is to fit a power curve to the measured data, and compare the curve constants. Of course, this approach is somewhat flawed, as it does not take into account the fact that there is a theoretical upper limit for most types of performance (Isokoski and MacKenzie, 2003). Steady state performance can be identified by performing statistical contrasts between blocks to find when the differences between the blocks stop being statistically significant (Douglas et al., 1999). Once steady state has been reached, overall learning can be quantified by comparing the percentage in improvement between steady state performance and initial performance.

In addition to quantitatively tracking performance over time, learning, and levels of intuitive input and ease-of-use information can be captured subjectively. Post-test questionnaires that ask users to rank statements such as "the device was easy to learn," can be very useful in determining to what degree the device provides intuitive input. These sorts of questions and free-form answers can give insight into what makes a device more or less intuitive, in addition to providing performance information. The questions used to determine the subjective learning characteristics of the Command Chair can be found in the Appendix B.

4.1.3 Measuring Comfort – Posture, Subjective Feedback

As discussed in the LBNL forearm support study in Chapter 2, EMG readings can be very useful in determining the relative comfort of a device. Since Chapter 2 demonstrated the benefits of forearm support for static muscle load (via EMG readings), other measures of comfort were used for this follow-up test.

During this study, the presence of forearm support was visually observed by the testers to alter the working wrist posture of subjects (see Figure 4.2.2). Unfortunately, the LBNL study was not designed to capture wrist posture data. To quantify this observed effect, wrist posture was an obvious candidate for consideration in this follow up study. Once again, wrist posture has been shown to correlate to risk of Musculoskeletal Disorders (Marcus et al., 2002, Bach et al., 1997, Keir et al., 1998). Therefore, it is an important measure when considering the long-term comfort of a workstation.

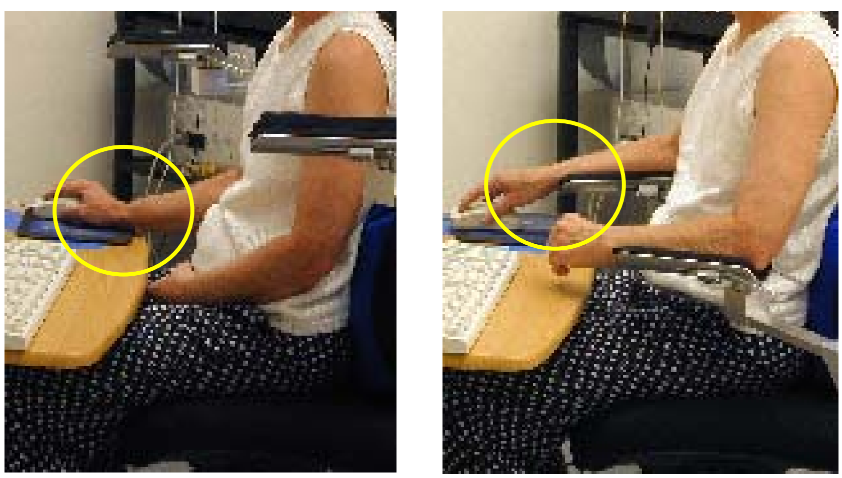


Figure 4.1.3: Observed Posture Changes for Mousing with LBL Forearm Support

Subjective measures are also a very important factor in considering comfort. Even if there is excellent quantitative data backing up the benefits of a device, if the users don't subjectively like the device (or think it's more comfortable), they will ultimately not use it. In other words, the perception of comfort is often more important than the quantitative measures that are available.

Some techniques for capturing subjective information regarding the comfort of a workstation were demonstrated in Chapter 2. Questionnaires are the most commonly used tool used to capture this type of qualitative information. For this test, comprehensive post-test questionnaires were provided to capture short answer, open-ended feedback, a rating of perceived exertion (Borg 1999), and feedback on subjective comfort and post-test fatigue ranked on a visual analog scale (see Appendix B for examples of these questionnaires).

The visual analog scale provides a continuous range of values for subjects to select. This allows subjective data to be treated as nominal, continuous data, rather than rank-order data. In turn, this allows for higher power statistical analyses to be used to analyze the data, and provides for a higher resolution in discriminating between results. An additional benefit of providing some open-ended questions is that participant answers can guide designers to the underlying causes or comfort or discomfort, rather than simply providing data about comfort level.

4.2: Experimental Design for the Command Chair Study

The Command Chair was tested with respect to pointing performance and total workstation throughput performance (including both typing and pointing). Performance of the Command Chair was tested in comparison to a traditional workstation with no forearm support, and a workstation with a fixed forearm support (a *Morency*™ rest). These workstation configurations are shown in Figure 4.2.1. The order of presentation of these devices was counterbalanced among test subjects in order to reduce the effects of learning across devices.

a) Command Chair

b) Fixed Forearm Support

c) Conventional Workstation

Figure 4.2.1: Compared Workstation Configurations

With the exception of a practice trial provided for the Command Chair, the tests for all three workstations were identical. Prior to testing, the practice trial allowed users to familiarize themselves with the Command Chair, a device that none of the subjects had previously used (in contrast to the mouse, with which all subjects had extensive experience).

For each device, subjects first performed six blocks of trials testing pointing speed and accuracy with a conventional Fitts' tapping test (described in section 4.1.1). This series was designed to capture learning effects in workstation performance. Next, subjects performed a single trial block testing combined pointing and homing. This test was identical to the standard Fitts' test, but was initiated by pressing the spacebar rather than clicking the mouse button. Homing time was measured as the time between the space bar depression to the time that the mouse started moving (while the dominant hand moved from the keyboard to the mouse). Finally, one block of the combined pointing, homing, and typing test was performed using the custom software described previously. The series of a) pointing, b) pointing with homing, and then c) pointing with homing and typing was repeated in order for each device. Since each participant repeated the test for all three workstation configurations, this was a within-subjects experimental design.

4.2.1 Fitts' Tapping Test

The Fitts' tapping test was performed using the GFLMB software described above, and the testing was designed to follow the guidelines of ISO standard 9241-9. Each test block consisted of 48 trials. Trials were presented in random order. Each trial was comprised of a combination of the following factors and levels (one instance of each combination per trial). These levels correspond to Index of Difficulties ranging from 2.6 to 6.3 – in the range recommended by previous studies and standards.

Target Width (W): 3mm, 6mm, 12mm

Distance to Target (A): 60mm, 120mm, 240mm

Angle to Target (α): 0°, 45°, 90°, 135°, 180°, 235°, 270°, 315°

The Fitts' task began on a mouse click, and required a user to move the cursor in the "angle to target" direction from the starting point to the center of a circular target. In order to capture keyboard-to-mouse homing time, the final pointing block (block 7) began on a press of the space bar, rather than a mouse click. Since this task was dramatically different, pointing times for the homing task were not compared with pointing times with no homing. Movement time and tap location (relating to accuracy) were captured for each trial to use in throughput calculations. Performance was tracked over the course of the six blocks in order to track improvement due to learning. Since all factor combinations were tested, this was a full-block experimental design.

4.2.2 Workstation Throughput

Custom combined point, home, and type test software was used to capture complete workstation throughput (as described in section 4.1.1). Using this software, the display screen was divided into 23 rows and 23 columns of cells. This resulted in a cell size of roughly .6 inches by .4 inches. Four colors of cell highlight were used: almond, yellow, orange, and purple. These colors were selected as they all consist of six letters and contain a combination of keys from both sides of the keyboard (requiring both the left and the right hand to type). The name of the color was provided in the highlighted cell in order to avoid confusion regarding the specifics of what color name was to be entered.

Fifty trials were presented for this test. All trials proceeded in an order generated by a random number generator. Since the trials all used the same seed number for the number generator algorithm, all trials followed the same sequence of conditions (highlighted cell location and color). Therefore, the same order and conditions were repeated for each workstation configuration – allowing for within-subjects comparisons.

Pointing time was measured as the time required between clicking on the homing cell, and clicking on the highlighted cell. To-keyboard homing time was measured as the time between clicking on the highlighted cell and typing the first character of the highlight color name. Typing time was defined as the time required from typing the first letter of the highlight color name to pressing the "Enter" key to signify completion. Note that subjects were instructed to *not* correct any typing errors (no backspacing). Finally, to-mouse homing time was measured as the time taken between pressing the "Enter" key at the completion of typing to the first motion of the mouse.

4.2.3 Participants and Environment

Twelve volunteer engineering graduate and undergraduate students participated in this study. All had extensive previous computer experience, and used the mouse primarily with their right hand. All participants were able to type with all fingers on the keyboard, although with varying degrees of mastery. The participants were all observed to plant their wrist on the table top while mousing. Participants were screened to insure that they could interact with a computer without pain for the duration of the test. Ten participants were male; two were female. A potential thirteenth subject's data was excluded prior to analysis due to procedural errors during the test (improper number of pointing blocks run and improper use of the Command Chair). Participant ages ranged from 21 to 30, and participant heights ranged from 5'2" to 6'6".

Mouse speed was set in Windows 2K at 6 out of 11 with no acceleration. This corresponded to a Controller:Display gain of roughly 1:5.5 for all workstation configurations. A convention Microsoft *Intellimouse* ball mouse was used for the conventional workstation configurations. A foldable membrane keyboard manufactured by Eumax was used for typing. This keyboard was selected as it was the same keyboard used in the construction of the Command Chair. Therefore typing differences between the workstations are due more to workstation configuration than keyboard specifics (i.e. key make force, tactile feedback, etc). Similarly, the same chair used in the construction of the Command Chair, the *Aeron*, was used for the comparison workstations. The testing system used a 19" monitor set to 1024x768 resolution.

Workstations were configured to personal preference by the participants prior to testing. Fixed parameters included the table height of 29 inches, monitor height of 6 inches to the bottom of the screen, and monitor position of 12.5 inches from the edge of the table. Participants were allowed to configure monitor angle, chair height, chair tilt, input device position, and lumbar support to their personal preference. It is important to note that the Command Chair arms cannot fit above or below the tabletop. Therefore, they must sit in front of the table top, pushing users further from the monitor than the other workstation configurations. Monitor viewing distance was measured to be approximately 11 inches greater for input with the Command Chair than input with the other workstation configurations – a potentially confounding factor.

4.2.4 Wrist Posture Measurements

Wrist posture measurements were taken using an electro-goniometer manufactured by Biometrics Ltd. This was a sensor that was taped to user's wrists, and provided two channels of output, one each for wrist extension and wrist deviation. The output signal from the amplifier was an analog voltage signal that linearly relates to the wrist angles. The voltage output equals 2.5 Volts + 1 Volt/(90° of motion) for each channel. Output accuracy was ±3° over ±90°. The device did not measure wrist pronation. Goniometer readings were sampled by a Data Acquisition Card at 4 Hertz. Data were sampled for the first two minutes of pointing Block 6 (representing practiced performance).

The goniometer was taped to the right wrist of the participants prior to testing. Wrists were place in a fixture to ensure consistent sensor placement (Figure 4.2.2). The sensor was calibrated while the fixture held the wrist in a neutral position. This insured a repeatable calibration position. A strap was wrapped around the participant's right upper arm to provide a strain relief for the wires, preventing them from applying any force to the sensor that might alter the readings.

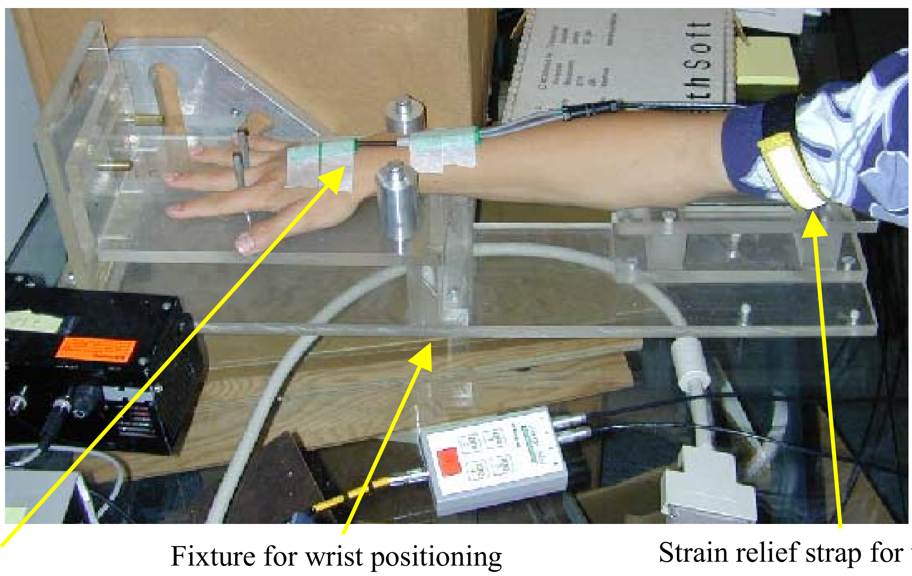


Figure 4.2.2: Electrogoniometer Attachment Fixture and Sensor Placement

4.3: Experimental Results

Since the experimental design was a within-subjects design, efficiency, throughput, learning, error, and goniometry results were first analyzed using repeated-measures ANOVA. Bonferroni post-hoc t-tests were then used when statistically significant differences were detected. Since subjective data is often non-parametric, the subjective questionnaire results were analyzed using the non-parametric Kendall's W method. Results from each sub-test are presented in sections 4.3.1 to 4.3.4.

Follow-up test results are presented in data tables 4.3.1 to 4.3.8. In these tables, results which share the same letter of a letter pair have been found to be significantly different ($p<.05$).

4.3.1 Fitts' Tapping Results

Fitts' tapping mean pointing times, throughput averages and the standard errors for both are shown in Table 4.3.1. Repeated-measures analyses revealed statistically significant differences for all four comparisons:

- Mean pointing times were found to be significantly different between workstation configurations ($F(2,22)=129.74$, $p < .05$).
- Mean pointing time standard errors of the mean were found to be significantly different between workstation configurations ($F(2,22)=73.29$, $p < .05$).
- Throughputs were found to be significantly different between workstation configurations ($F(2,22)=97.55$, $p < .05$).
- Throughput standard errors of the mean were found to be significantly different between workstation configurations ($F(2,22)=13.18$, $p < .05$).

Individual comparison differences are also shown in Table 4.3.1. Standard errors of the mean are shown in parentheses.

	Command Chair	**Fixed Support**	**Mouse**
Mean Movement Time (ms)	2214 [a,b]	1363 [a]	1395 [b]
Mean Movement Time Standard Error (ms)	(902) [f,g]	(430) [f]	(444) [g]
Throughput (bits/time)	1.95 [d,e]	3.44 [d]	3.48 [e]
Throughput Standard Error (bits/time)	(.30) [h,i]	(.44) [h]	(.38) [i]

Results which share letter pairs are significantly different statistically: $p<.05$, $N=12$

Table 4.3.1: Average Pointing Speeds (Time and Throughput)

As expected, the pointing performance of the Command Chair was found to be slower than workstations using a mouse as the primary pointing device. Interestingly, the presence of the fixed forearm support did *not* significantly affect the mean movement time or throughput of the participant's mouse use. These findings will be discussed more thoroughly in section 4.4.1. Figure 4.3.1 presents these findings as a boxplot showing the mean pointing times and distribution results from the Fitts' tapping experiments. In this graph, the shaded box represents the 25^{th} to 75^{th} quartile range, the horizontal line is the median value, and the whiskers represent the maximum and minimum observed values.

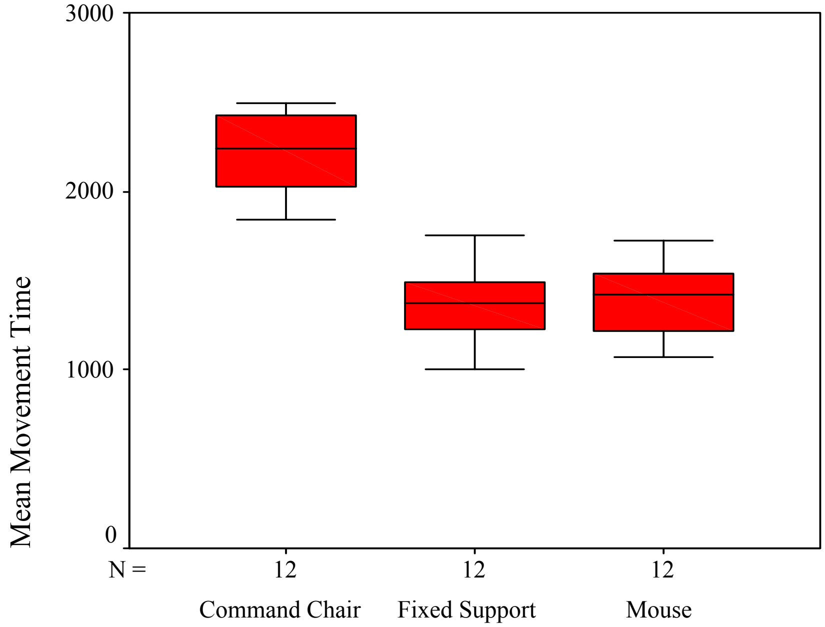


Figure 4.3.1: Mean Movement Times Boxplot

Note that much of the contribution to the large standard deviations comes from performance differences *between* users. However, this portion of the deviation is removed from statistical analysis consideration by using the repeated-measures experimental design. This holds for the standard deviations in all of the results.

Learning effects over the course of the Fitts' experiment are shown in Figures 4.3.2 and 4.3.3 (for mean movement time and throughput, respectively). These graphs reiterate the findings that the presence of the fixed forearm support has no statistically significant effect on the pointing performance of the mouse. They also show the performance differences between the Command Chair and mouse-based systems as a function of repetition.

It is also interesting to note that the bulk of the learning for the mouse-based systems occurred within Block 1. This is most likely due to task familiarization, rather than input device based learning (since all of the test participants were expert mouse users prior to beginning this test).

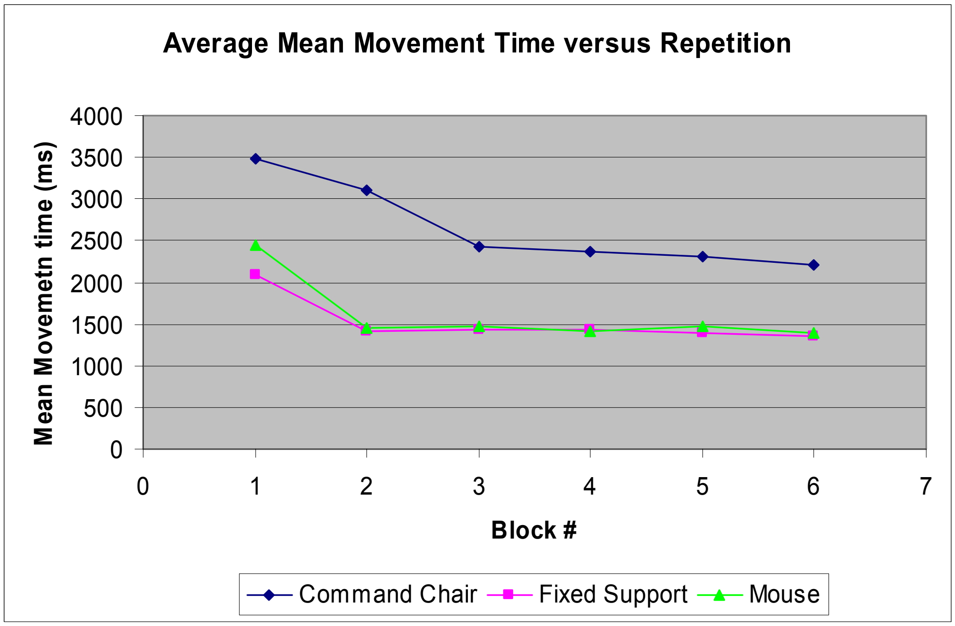


Figure 4.3.2: Mean Movement Time with Repetition

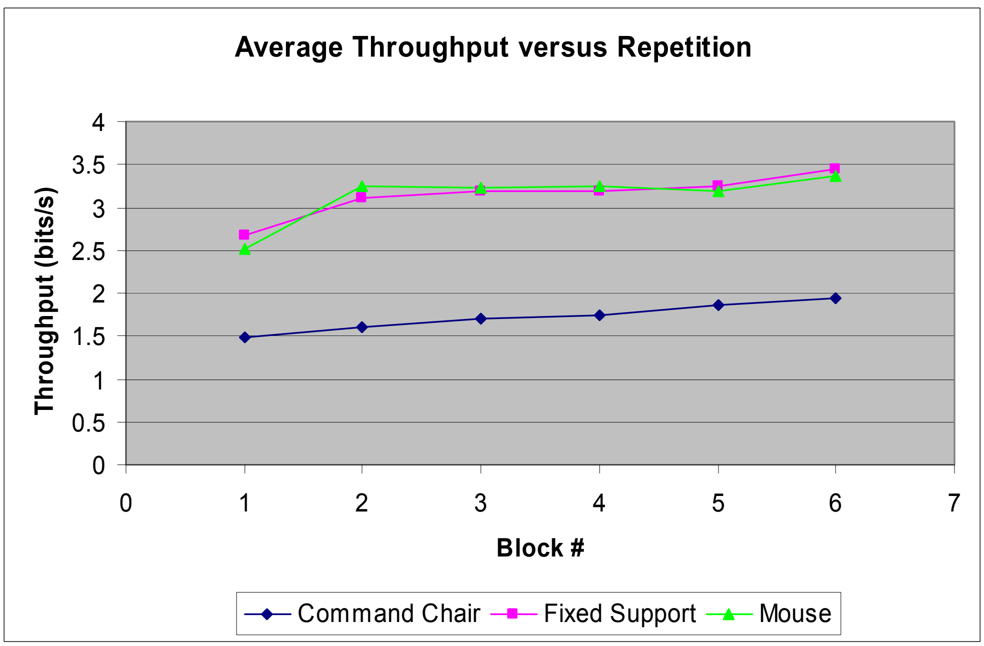


Figure 4.3.3: Mean Throughput with Repetition

Consistent progress over the course of the experiment is shown in the throughput graph of Command Chair performance over time (Figure 4.3.3). This is an interesting thing to note because it is slightly different than the similar graph for mean movement time, which shows a steep learning curve over blocks 1-3, which then flattens out for the remainder of the test. This difference in throughput is caused by the difference in accuracy between blocks. So, while the movement time decreases rapidly at the start of the test, a decrease in accuracy accompanies it. As accuracy stabilizes over the course of the test, the throughput continues to increase at a steady rate.

No statistically significant differences were observed in pointing performance between blocks beyond block 4 – indicating that steady state performance had been reached after block 4 (192 repetitions). Block performance (to determine steady-state performance) was compared using pairwise t-tests. This finding supports the use of Block 5 and 6 averages as a metric for practiced performance.

Despite the lack of statistical significance, it is still important to note the trend towards improved throughput performance for the Command Chair past block 4. This is because a linear curve fit shows an R^2 value of 99%, meaning the curve does not show a trend towards flattening out (as one would typically expect for practiced performance).

Learning rates shown as improvement percentages are shown in Table 4.3.2. For mean movement times, these were calculated by subtracting the mean movement times of the average of the first two blocks of repetitions from the average of the final two blocks of repetitions, and then dividing by the first block's results to normalize to a percentage. Averaging block performance was done to insure a more robust result, since individual block results were found to be quite volatile. One outlying data point was removed from the Command Chair throughput learning comparison. This data point for user ten was an order of magnitude higher than any of the other observed data, and was caused by that participant's slow device familiarization early in the test (Blocks 1 and 2).

	Command Chair	Fixed Support	Mouse
Mean Pointing Time Improvement	17.3 %	16.8 %	17.2 %
Mean Pointing Time Improvement Standard Error	(23.6 %)	(16.5 %)	(23.2 %)
Throughput Improvement	17.5 %	19.0 %	21.5 %
Throughput Improvement Standard Error	(19.0 %)	(15.7 %)	(24.6 %)

Table 4.3.2: Percent Improvement with Learning Over the Course of the Experiment

None of the mean pointing time improvements were found to show statistically significant differences between workstation configurations ($F(2,22)=.003$, $p>.05$). Similarly, none of the throughput improvements were found to show statistically significant differences between workstation configurations ($F(2,22)=.122$, $p>.05$). This means that learning percentages are not significantly different between the different workstations. The reason for no statistically significant findings is most likely a combination of two factors. First, the Command Chair was designed to follow a very intuitive pointing metaphor, simply mapping input device position to virtual pointer position. This helps to make for a more intuitive device, showing lesser learning effects. This theory is bolstered by the subjective findings, which indicate that the participants felt that the device was easy to learn (see section 4.3.4 for details). Second, there was a very high standard error observed for learning measurements, reducing the chances for finding significance. The results may also change if Block 1 performance were neglected to remove the effects of task-based learning.

	Command Chair	Fixed Support	Mouse
Error Rate	12.33 % [a]	5.03 % [a]	5.21 %
Standard Deviation	(7.19 %)	(2.58 %)	(5.14 %)

letter pairs denote significant differences: $p<.05$, N=12

Table 4.3.3: Error Rates

Error rates are shown in Table 4.3.3, and were found to show statistically significant differences between workstation configurations ($F(2,22)=207.7$, $p<.05$). However, follow-up tests revealed that statistically significant differences only existed between the Command Chair and the Fixed Support systems. This is most likely due to the high standard deviations shown for the Command Chair and mouse conditions. A higher power test would most likely reveal statistically significant differences in error rate between the Command Chair and mouse conditions, as well.

A possible outlier was noted for the Command Chair condition. User 12 performed with an error rate of almost 30% — almost three times the average value. If this outlier is removed from the analysis, the average error rate for the Command Chair drops to 10.8%, with a standard deviation of 5.09% (a drop of almost 2 percentage points for both mean and standard deviation). This exclusion does not change the significance findings for this task, and the error rate for the Command Chair remains almost double the error rate for the other input systems. However, for a more conservative analysis, this data point was not removed in the presented results.

While accuracy findings are included in the throughput findings previously presented, it is worthwhile to separately and specifically discuss error rate. This is because consideration of error rate gives greater insight into the specifics of device performance, rather than looking at a single clumped metric (throughput), which makes device performance comparison simple, but obscures some of the details involved.

In this case, the Command Chair mean error rate was measured as being quite high relative to the other systems. Clearly, this is an issue to be addressed in trying to improve system throughput in the future. See Section 4.4.1 for more discussion on this topic.

4.3.2 Homing Time Results

Average homing times (measured as the time required to move the hand from the keyboard space bar to the mouse) were found to be significantly different between workstation configurations ($F(2,22)=1158.6$, $p < .05$). Similarly, homing time standard errors were also found to be significantly different between workstation configurations ($F(2,22)=517.2$, $p < .05$). Table 4.3.4 shows the specific findings, as well as the results from follow-up comparisons.

These findings verify that one of the design intents of the Command Chair has been met — reducing homing time. This finding is not only statistically significant, it also demonstrates a very large effect size with over an order of magnitude in homing time reduction. In addition to the homing time reduction, the standard error of homing time is also much smaller than the standard error for the other workstations, and the difference is statistically significant. This means that the homing time of the Command Chair is also more consistent in addition to being faster.

	Command Chair	**Fixed Support**	**Mouse**
Average Homing Time (ms)	52 [a,b]	638 [a]	597 [b]
Homing Time Standard Error (ms)	(55) [d,e]	(128) [d]	(94) [e]

letter pairs denote significant differences: $p<.05$, $N=12$

Table 4.3.4: Space Bar Homing Time Results

Figure 4.3.4 presents these homing time findings as a boxplot showing the mean homing times and distribution results. For this graph, the shaded box represents the 25th to 75th quartile range, the horizontal line is the median value, and the whiskers represent the maximum and minimum observed values.

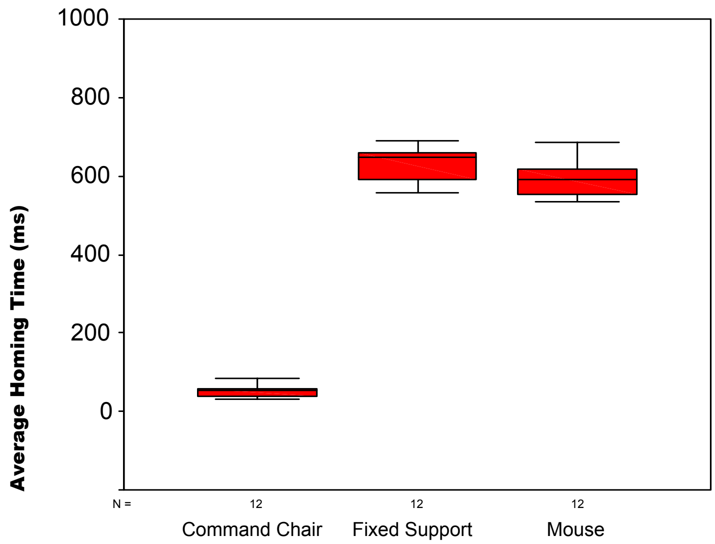


Table 4.3.4: Space Bar Homing Time Results

4.3.3 Workstation Throughput

The combined pointing and typing task measured tapping mean pointing times, homing time to keyboard, typing time, and homing time to mouse, and total task time as well as the accompanying standard errors. These findings are shown in Table 4.3.5.

Operation	**Command Chair**		**Fixed Support**		**Mouse**	
	Time (ms)	standard error (ms)	Time (ms)	standard error (ms)	Time (ms)	standard error (ms)
Pointing	2237 [a,b]	(1073) [i,j]	1322 [a]	(230) [i]	1340 [b]	(288) [j]
Homing to Keyboard	1072	(320) [k]	1013	(253)	968	(196) [k]
Typing	2679 [c,d]	(870) [l,m]	1322 [c]	(456) [l]	1277 [d]	(408) [m]
Homing to Mouse	132 [e,f]	(181)	655 [e]	(121)	626 [f]	(110)
Total	6120 [g,h]	(2444) [n,o]	4311 [g]	(1060) [n]	4210 [h]	(1001) [o]

letter pairs denote significant differences: $p<.05$, N=12

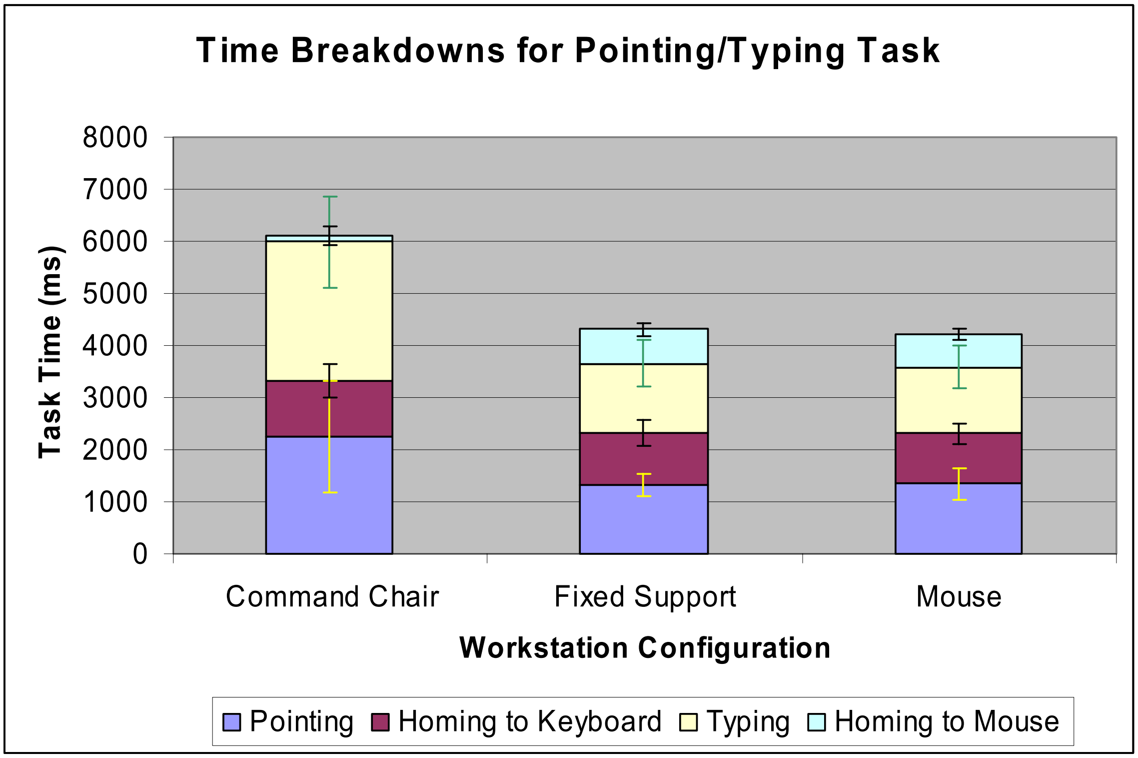
Table 4.3.5: Combined Pointing/Typing Time Results

Repeated-measures analyses revealed statistically significant differences for all five time comparisons, except for homing time to the keyboard:

- Mean pointing times were found to be significantly different between workstation configurations ($F(2,22)=131.1$, $p < .05$).
- Homing times to the keyboard were *not* found to be significantly different between workstation configurations ($F(2,22)=1.7$, $p > .05$).
- Typing times were found to be significantly different between workstation configurations ($F(2,22)=26.3$, $p < .05$).
- Homing times to the mouse were found to be significantly different between workstation configurations ($F(2,22)=190.2$, $p < .05$).
- Total task times were found to be significantly different between workstation configurations ($F(2,22)=24.4$, $p < .05$).

Table 4.3.5 also presents the location of statistically significant differences revealed by follow-up comparisons as denoted by letter pairs. All standard error comparisons were found to be statistically significant, with the exception of the standard error for homing to the mouse.

Figure 4.3.5 presents the relative contribution from each phase of the task to the total task time of the combined pointing and typing task. The Command Chair required significantly more time on average to complete the task than either of the other workstation configurations. This required time for the Command Chair was dominated by the typing time, followed by the pointing time. In addition to contributing the largest times, these phases also contributed very large standard errors for the Command Chair.



Error bars represent one standard error. N=12

Figure 4.3.5: Time Contributions for Combined Pointing and Typing Task

The findings for increased pointing time are in line with the findings of the Fitts' tapping test. It is interesting to note that, once again, the presence of the fixed forearm support did not significantly affect the pointing performance of the mouse. Typing and homing times were similarly unaffected by the presence of the fixed forearm support. This finding bolsters the argument for fixed forearm support as it had no deleterious effect on performance and provides increased system comfort via forearm support.

The magnitude of typing time for the Command Chair is very high relative to the other workstation configurations. There are likely several contributing factors to this. First, the fact that the Command Chair provides a keyboard that is completely split makes typing more difficult for some users. In particular, users that must look at the keyboard in order to locate the desired keys are placed at a disadvantage with the Command Chair. This is because the physical distance between the keyboard halves makes key target acquisition more difficult and time consuming – especially for words that require key combinations from both keyboard halves (like those chosen for testing). These findings are similar to previous studies examining a support device that provided a fully split keyboard. In that study, typing speed was also found to be slightly reduced for the support device, particularly for hunt-and-peck typists (Hedge and Shaw, 1996).

Several subjects were observed to look back and forth from keyboard halves trying to identify the necessary keys. On the other hand, several subjects were also observed to type with no trouble on the Command Chair keyboards, while maintaining their gaze on the computer monitor. For this reason, it appears that the Command Chair would be best suited for touch-typists who are comfortable with split keyboards (which may come down to personal preference). These differences between users show up in the large standard error measured for typing.

The second likely reason for the differences observed in typing performance between workstation configurations is that typing learning effects were not considered in this experiment. Many subjects commented that they had some trouble initially getting accustomed to typing on the Command Chair. This is consistent with observations of users interacting with the device, who seemed to perform better with the device at the end of the trial than at the beginning. For this reason, it is expected that typing performance on the Command Chair would improve with familiarity and practice.

Another interesting finding from the workstation throughput test is the asymmetry found in homing times to the keyboard and to the mouse. Pairwise t-tests found statistically significant differences between to keyboard and to mouse homing times for all three workstation configurations.

The homing time asymmetry seems to have a reasonable explanation when considering the precision and attention required to home to the keyboard versus the mouse. The mouse is a single object on which the whole hand sits. It is large and can easily be located by feel, muscle memory of its last location, and peripheral vision. In contrast, homing to the "home" row of the keyboard requires more attention. It is surrounded by visually similar keys, and the four fingers must be individually homed, rather than just the hand as a whole. Also, there is little tactile feedback available as to the proper position of the hand on the keyboard relative to what is available to the mouse.

Homing asymmetry is most pronounced in the Command Chair. In this case, the forearm is always located on a forearm rest, which can serve as motion input. Therefore, it requires very little time to home to the mouse from the keyboard. However, homing to the keyboard is still similar to regular keyboard homing. This is because the fingers must still be precisely located over the home row. Even though the distance to the keyboard is reduced with the Command Chair, the tracking and cognitive requirements to locate the proper hand position dominate the homing time over the moving time.

Note that the pointing time to return to the homing cell at the end of the trials was not considered in the analysis. This is because this time was used to provide users with a break in between trial times – so the times would be artificially skewed. Fitts' law predicts that this return pointing time would be identical to the initial pointing time. So this secondary measure would most likely be redundant.

Error Type	Command Chair		Fixed Support		Mouse	
	Error Rate(%)	standard error	Error Rate(%)	standard error	Error Rate(%)	standard error
Pointing Error	12 % [a,b]	(30 %) [i,j]	3 % [a]	(15 %) [i]	5 % [b]	(18 %) [j]
Typing Error	31 % [c,d]	(45 %) [k,l]	16 % [c]	(32 %) [k]	16 % [d]	(32 %) [l]
Total Error	43 % [e,f]	(56 %) [m,n]	19 % [e]	(37 %) [m]	21 % [f]	(39 %) [n]

letter pairs denote significant differences: $p<.05$, $N=12$

Table 4.3.6: Combined Pointing/Typing Error Results

In addition to tracking the times required to complete the combined pointing and typing task, the test software also tracked the pointing, typing, and total error rates. Statistically significant differences in the error rates for the three different workstation configurations were found for pointing error ($F(2,22) = 12.44$, $p<.05$), typing error ($F(2,22) = 22.17$, $p<.05$), and total error ($F(2,22) = 32.49$, $p<.05$). Similarly, statistically significant differences in the standard error of the error rates for the three different workstation configurations were found for standard error of pointing error rage ($F(2,22) = 9.53$, $p<.05$), standard error of typing error ($F(2,22) = 11.38$, $p<.05$), and standard error of total error ($F(2,22) = 19.72$, $p<.05$). These results are summarized in Table 4.3.6.

For the complete workstation test, a pointing error was recorded whenever any cell other than the highlighted cell is selected. Similarly, typing errors occurred whenever any word other than the correctly spelled color highlight name was entered. Note that subjects were instructed *not* to correct any mistakes as they typed (i.e. no backspacing). This was done to remove error-correction as a confounder of typing times.

Pointing error rates were similar for all workstation configurations to those measured in the Fitts' tests, verifying those pointing error results. Typing error rates were quite high overall, with the Command Chair demonstrating a typing error rate roughly double that of the other workstation setups. As previously discussed, it is likely that unfamiliarity with typing on the Command Chair played a large factor in these high error rates. Several subjects commented that it took a portion of the pointing/typing task to become comfortable with typing on the Command Chair. This is consistent with tester observations, which noted a higher error rate at the beginning of typing tests for many subjects, which seemed to diminish with familiarity.

No typing practice was provided prior to this test. The lack of practice likely had a much larger effect for the performance of the unfamiliar device (the Command Chair), than for the familiar device (the traditional unsplit keyboard).

4.3.4 Wrist Posture Measurements

Wrist posture averages and standard errors are shown in Table 4.3.7. Repeated-measures analyses revealed statistically significant differences for all four comparisons:

- Wrist extension angles were found to be significantly different between workstation configurations ($F(2,22)=34.24$, $p < .05$).
- Wrist radial deviation angles were found to be significantly different between workstation configurations ($F(2,22)=6.71$, $p < .05$).
- Wrist extension standard errors were found to be significantly different between workstation configurations ($F(2,22)=6.79$, $p < .05$).
- Wrist radial deviation standard errors were found to be significantly different between workstation configurations ($F(2,22)=22.79$, $p < .05$).

	Command Chair	Fixed Support	Mouse
Wrist Extension Averages	9.2° [a,b]	22.5° [b,c]	31.6° [a,c]
Wrist Extension Standard Error	(1.4°) [f,g]	(3.2°) [f]	(3.5°) [g]
Wrist Radial Deviation Averages	9.8° [d,e]	-1.0° [d]	1.5° [e]
Wrist Radial Deviation Standard Error	(1.6°) [h,i]	(4.8°) [h]	(5.4°) [i]

letter pairs denote significant differences: $p<.05$

Table 4.3.7: Wrist Posture Averages and Standard Errors

Wrist extension was found to be dramatically reduced with the presence of forearm support, giving even more weight to the argument for providing forearm support for workstation comfort. The fixed support condition reduced average wrist extension by almost 10°, while the Command Chair reduced it by over 20° relative to a traditional mouse. This provides verification that one of the design goals of the Command Chair – "a more neutral wrist position" has been met. This is an important result, as previous findings have recommended wrist extension to remain less than 10° (Zecevic et al., 2000) for reduced risk of Musculoskeletal Disorder. In this study, only the Command Chair was found to meet this recommendation. Additionally, the Command Chair was shown to provide good control of wrist position, as evidenced by the low standard errors in wrist postures for this device. This feature of the Command Chair could be used to further reduce wrist extension, if so desired in the future.

Unfortunately, radial deviation was found to be much higher on average for the Command Chair than either of the other workstation configuration. This is a result of the Command Chair keyboard placement being set too far inward from the forearm supports. This deviation of ~10° is in a grey area for MSD risk. Some research suggests that deviations less than 20° are still in the safe range (Bach et al., 1997), while other research indicates that deviations as low as 5° may be dangerous (Zecevic et al., 2000). However, since good control of wrist deviation is also shown for the Command Chair (by the low standard error for the Command Chair wrist postures) – this problem can be easily corrected by re-aligning the keyboard further outward from the forearm rest.

Note that radial deviation and ulnar deviation represent the same motion in opposite directions. So, in the case of Fixed Support, -1° of radial deviation more accurately represents 1° of ulnar deviation.

Typical wrist postures charted as a function of time are shown in Figure 4.3.6. The meaning of the statistically significant differences found between the standard errors of the different workstation configurations can be clearly seen in this chart. Input motions using the Command Chair are much smoother and more consistent over time than for the other input stations. This smoothness is also reflected in the reduced standard error seen for wrist position for the Command Chair. This is an important finding because it demonstrates once again that the Command Chair provides better control of wrist posture relative to the other workstation configurations.

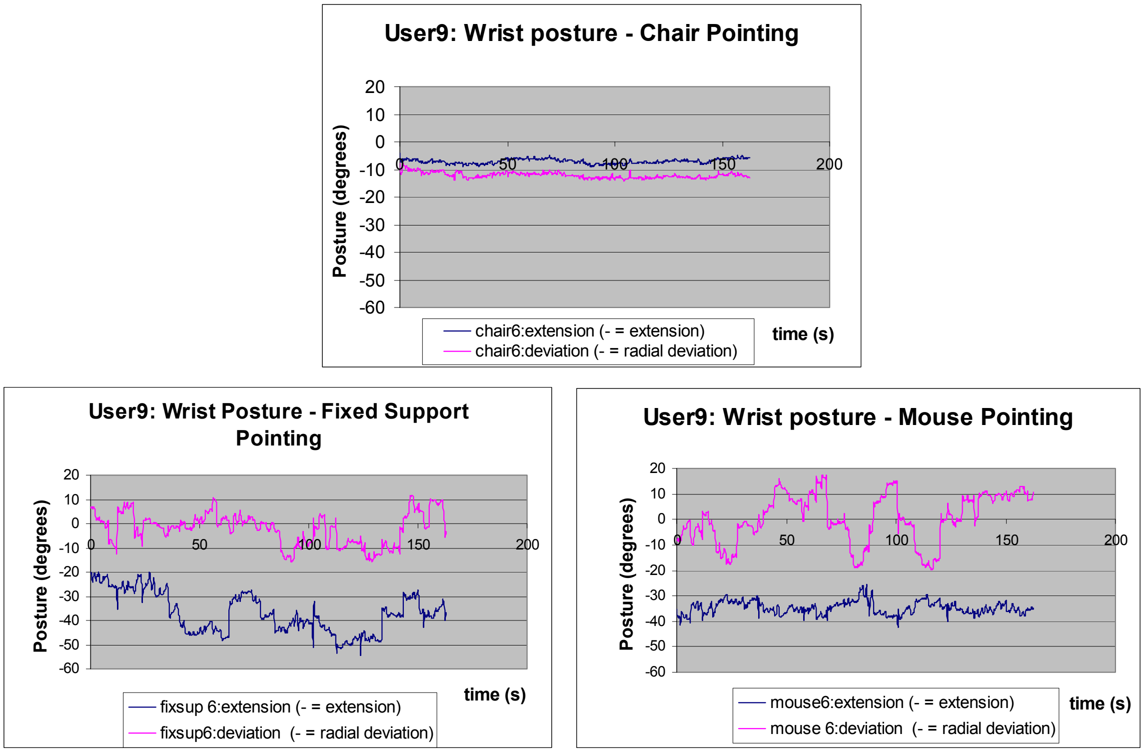


Figure 4.3.6: Typical Wrist Postures over Time

4.3.5 Questionnaire Results

Questionnaire results are summarized in tables 4.3.8 to 4.3.10. The original questionnaires can be found in Appendix B. As previously mentioned, the questionnaire was divided into 3 sections: rating of perceived exertion, free-form short answer questions, and ranking questions on a Visual Analog Scale. These results of these sections are individually presented and discussed.

	Arm Effort		Shoulder Effort		Neck Effort	
	Mouse	Command Chair	Mouse	Command Chair	Mouse	Command Chair
Average Rating	3.5	2.2	1.2	3.2	1.5	1.0
Standard Deviation	(2.8)	(1.3)	(.9)	(2.1)	(1.5)	(1.3)
Significant Difference? (p<.05)	No		Yes		No	

lower scores indicate lower perceived effort (non-linear scale)

Table 4.3.8: Rating of Perceived Exertion Results

Rating of perceived exertion results were compared using non-parametric pairwise Wicoxon tests. Both arm and neck effort results showed trends to reduction with the Command Chair (table 4.3.8). However, the experimental design was unable to discern statistically significant differences for these measures. A higher powered test (e.g. more subjects) would be required to identify significance in these results. Users indicated that required shoulder effort was significantly higher with the Command Chair than with a traditional mouse. This is an expected result, as Command Chair was specifically designed to shift input loads from the wrists to the shoulder.

Short answer results were categorized by recurring themes, and are presented in Table 4.3.9. Since these are free-form answers and no two were identical, no statistical tests were performed. Chi-squared tests for frequency were considered for evaluation, but the power of these tests would be very low, due to the small number of data points. Short answer questions were broken into three categories: learning, practiced skill, and overall impressions.

<table>
<tr><th colspan="12">Was the Command Chair easy to learn?</th></tr>
<tr><td colspan="6">easy</td><td colspan="6">hard</td></tr>
<tr><td colspan="6">11</td><td colspan="6">1</td></tr>
<tr><th colspan="12">How does learning the Command Chair compare with learning a mouse?</th></tr>
<tr><td colspan="4">similar</td><td colspan="4">harder</td><td colspan="4">don’t know</td></tr>
<tr><td colspan="4">4</td><td colspan="4">7</td><td colspan="4">1</td></tr>
<tr><th colspan="12">What was hardest to learn about the Command Chair?</th></tr>
<tr><td colspan="3">Pointing precision</td><td colspan="3">Limited motion range</td><td colspan="3">Split keyboard</td><td colspan="3">Soft keyboard</td></tr>
<tr><td colspan="3">4</td><td colspan="3">3</td><td colspan="3">4</td><td colspan="3">2</td></tr>
<tr><th colspan="12">At the end of the study, could you control the Command Chair?</th></tr>
<tr><td colspan="4">Pointing problems</td><td colspan="4">Other problems</td><td colspan="4">yes</td></tr>
<tr><td colspan="4">6</td><td colspan="4">3</td><td colspan="4">3</td></tr>
<tr><th colspan="12">Was Command Chair comfortable to use?</th></tr>
<tr><td colspan="6">yes</td><td colspan="6">no</td></tr>
<tr><td colspan="6">8</td><td colspan="6">4</td></tr>
<tr><th colspan="12">If you could use the Command Chair at your workstation, would you?</th></tr>
<tr><td colspan="6">yes</td><td colspan="6">no</td></tr>
<tr><td colspan="6">5</td><td colspan="6">7</td></tr>
<tr><th colspan="12">What applications would be well-suited to the Command Chair?</th></tr>
<tr><td colspan="4">Word Processing</td><td colspan="4">Spreadsheets</td><td colspan="4">Video Games</td></tr>
<tr><td colspan="4">2</td><td colspan="4">5</td><td colspan="4">6</td></tr>
<tr><th colspan="12">Under what circumstances would someone prefer the Command Chair?</th></tr>
<tr><td colspan="4">RSI sufferers</td><td colspan="4">Specific applications</td><td colspan="4">Touch typists</td></tr>
<tr><td colspan="4">1</td><td colspan="4">9</td><td colspan="4">1</td></tr>
<tr><th colspan="12">What did you like about the Command Chair?</th></tr>
<tr><td colspan="3">Comfortable</td><td colspan="3">No Fatigue</td><td colspan="3">Intuitive</td><td colspan="3">Fixed Hand Position</td></tr>
<tr><td colspan="3">4</td><td colspan="3">3</td><td colspan="3">2</td><td colspan="3">4</td></tr>
<tr><th colspan="12">What did you dislike about the Command Chair?</th></tr>
<tr><td colspan="4">Pointing Problems</td><td colspan="4">Typing Problems</td><td colspan="4">Distance to Screen</td></tr>
<tr><td colspan="4">11</td><td colspan="4">7</td><td colspan="4">1</td></tr>
<tr><th colspan="12">Do you have any suggestions to improve the Command Chair?</th></tr>
<tr><td colspan="3">Better bearings</td><td colspan="3">Fixed typing</td><td colspan="3">Better keyboard</td><td colspan="3">More adjustable</td></tr>
<tr><td colspan="3">8</td><td colspan="3">5</td><td colspan="3">3</td><td colspan="3">2</td></tr>
<tr><th colspan="12">How does the Command Chair compare to the Fixed Forearm Support?</th></tr>
<tr><td colspan="4">Less Effective</td><td colspan="4">More Comfortable</td><td colspan="4">Less Comfortable</td></tr>
<tr><td colspan="4">4</td><td colspan="4">5</td><td colspan="4">1</td></tr>
</table>

Table 4.3.9: Summary of Short-Answer Question Results – Response Frequency

The learning results indicate that the Command Chair is easy to learn, although users felt that it was still harder to learn than a mouse (a device with which they were already expert). People were split as to whether the pointing performance or keying performance was more difficult to learn. An equal number of participants struggled with learning precision pointing as learning to use the split keyboard.

At the completion of the study, half of the participants felt like they still had trouble controlling the pointing of the Command Chair, bolstering the idea that longer-term practice may be necessary to achieve device mastery. The majority felt that the Command Chair was comfortable to use. Two of the participants who felt that the Command Chair was uncomfortable to use were the smallest test participants. These participants visually looked undersized in the chair (they would probably have normally selected a smaller sized base chair than the one provided), and the armature distance seemed to be too wide for their comfort. Clearly, future versions of the Command Chair would need to be able to better accommodate smaller users (either through multiple sizes, or greater adjustability).

A very promising result is that nearly half of the participants would choose to work on the Command Chair at their own workstation if provided the opportunity. This is a very strong indication of device preference, and shows the market potential for the Command Chair. The favorite characteristics of the Command Chair all related to comfort: the comfort itself, the prevention of fatigue, and the fact that the hand is held in a constant and neutral position. Conversely, the least favorite characteristics of the Command Chair all related to the reduced efficiency for both typing and pointing noted earlier. Users were split in comparisons of the Fixed Support versus the Command Chair.

Users made several suggestions to improve the aspects of the Command Chair they disliked. In particular smoother bearings were suggested to improve pointing performance, and better keyboards (with more tactile feedback) were suggested to improve typing performance.

Subjective rating results based on the visual analog scale were compared using Kendall's W tests (rank-order, non-parametric tests), and these results are shown in Table 4.3.10. For these ratings, a lower score indicates superior workstation performance, and an asterisk denotes statistically significant differences. Values in parenthesis represent standard deviations.

Device Property	**Command Chair**	**Fixed Support**	**Mouse**
ACTUATION FORCE *	**1.8** (1.3)	**.8** (.7)	**.8** (.9)
SMOOTHNESS *	**3.6** (.9)	**.8** (.6)	**1.0** (.8)
MENTAL EFFORT *	**2.1** (1.2)	**.8** (.7)	**.7** (.6)
PHYSICAL EFFORT *	**1.6** (1.2)	**.8** (.7)	**1.2** (1.0)
ACCURATE POINTING *	**2.9** (1.1)	**.5** (.4)	**.9** (.5)
DEVICE SPEED *	**3.2** (1.3)	**1.7** (1.0)	**2.0** (1.0)
FINGER FATIGUE	**1.3** (1.2)	**1.5** (1.4)	**1.7** (1.6)
WRIST FATIGUE *	**.5** (.5)	**1.7** (1.4)	**2.5** (1.3)
ARM FATIGUE	**1.3** (1.0)	**1.33** (1.1)	**1.8** (1.4)
SHOULDER FATIGUE *	**2.0** (1.4)	**.8** (.6)	**1.2** (1.1)
NECK FATIGUE	**.6** (.7)	**.7** (1.0)	**1.1** (1.6)
GENERAL COMFORT	**1.4** (1.1)	**1.3** (1.2)	**1.9** (1.1)
EASE OF USE *	**2.1** (1.0)	**.7** (.7)	**.8** (.7)

asterisks (*) denote significant differences: p<.05, N=12

0 = Better/More Preferred *5 = Worse/Less Preferred*

Table 4.3.10: Subjective Results based on the Visual Analog Scale

Most of these findings verify quantitative findings, such as device speed and accuracy. It is encouraging to note that users seem to be able to discern workstation performance differences, verifying the usefulness of subjective measures of performance. None of these results are very surprising given the previously presented quantitative findings. Most notable is that users did notice that the device transfers input motions from the wrist to the shoulder – resulting in the subjective findings of reduced wrist fatigue and increased shoulder fatigue for the Command Chair.

4.4: Command Chair Performance Discussion

These results demonstrate some of the performance differences between the three workstation configurations. By experimental design, these performance differences fall along the metrics of greatest interest: efficiency, intuitive input, and comfort.

4.4.1 Device Efficiency

The pointing performance results from Table 4.3.1 have been used to calculate relative performance percentages for each of the three possible workstation comparisons. Relative performance is very useful for making simple comparisons between workstation performances.

Device Comparison	**Normalized Pointing Time**	**Normalized Throughput**
Command Chair - Mouse	37.0 %	42.0 %
Command Chair – Fixed Support	38.5 %	43.4 %
Mouse – Fixed Support	2.3 %	2.3 %

Table 4.4.1: Relative Performance Percentages

As shown in Table 4.4.1, the Command Chair demonstrated mean pointing time performance that was 37% slower than a traditional mouse. The two-dimensional pointing performance of the Command Chair is roughly equivalent to a pointing device currently in use – the isometric joystick (Douglas et al., 1999). This is a good improvement over the Command Chair prototype presented in Chapter 3, which demonstrated mean pointing time performance that was roughly 50% slower than a traditional mouse (Odell and Wright, 2003). This improvement is even more impressive than the numbers indicate, because the current experiment required that the devices be controlled simultaneously in two dimensions. This is a more rigorous test than the Command Chair prototype was put to, where control in only one dimension was required. So, the new caster-cart concept for the Command Chair has succeeded in dramatically improving pointing performance.

Even more encouraging is the fact that the present experiment revealed specific areas of potential improvement for the pointing and typing performance of the Command Chair. As mentioned by the test participants and noticed by the author, pointing performance was somewhat inhibited by the bearing selection of the Command Chair. The recirculating bearings seemed to have dead spots – providing extra resistance to motion at that spot. It appeared that these dead spots occurred was caused by uneven spacing of the recirculating bearings on the rotating ball transfer. Dirt may have also played a role in creating the dead spots. The dead spots resulted in some waver appearing in the motion of the Command Chair as the user attempted to move in a straight line. Worse, occasionally, the dead spots situated directly on top of the virtual target – making it quite difficult to move into the target to select it (and artificially reducing pointing speed). So, locating better bearings with no dead spots could serve to dramatically improve pointing performance.

Another idea presented by many of the test participants was to provide a better way of splitting large scale and small scale pointer motions. They felt that the mouse provided the facility to move the entire arm for large scale motions, and then plant the wrist to provide stability for making fine motions with the fingers. However, this capability is not currently available in the Command Chair. It could be provided through a range of solutions – from providing a *Trackpoint*™ in the keyboard, to adding a joint to the forearm support to allow for a small amount of separate wrist motion.

Device Comparison	**Normalized Completion Time**
Command Chair – Mouse	31.2 %
Command Chair – Fixed Support	29.6 %
Mouse – Fixed Support	2.3 %

Table 4.4.2: Relative Completion Time Percentages for Combined Pointing/Typing Task

Table 4.4.2 presents between-device comparison percentages for the combined pointing/typing task designed to quantify complete workstation performance. As can be seen, the complete workstation performance of the Command Chair is somewhat better than simple pointing alone. The difference between this performance and simple pointing is the inferior typing speed of the Command Chair relative to the other workstations, somewhat offset by the greatly improved keyboard-to-mouse homing time.

The first step in trying to improve the typing time of the Command Chair would be to provide participants some practice time so that steady-state, rather than initial, typing times would be tested. While this approach would not entirely address the issue, it would likely help significantly. In addition to practice, using a keyboard that provided better tactile feedback would likely be a great aid to improving typing time. Providing a mobile palm rest might also help somewhat. Beyond this, there may be little that can be done, as the very large distance between the keyboard halves is likely to have a negative effect on typing times in general (particularly for hunt-and-peck typists). Still, it is expected that these changes would greatly ameliorate some of the typing difficulties that some of the participants experienced.

In addition to verifying the reduced keyboard-to-mouse homing time of the Command Chair relative to other workstations, the homing time results from this study have verified the previously unverified theory that there is an asymmetry in homing from the keyboard to the mouse, versus homing from the mouse to the keyboard (Douglas and Mithal, 1994). This theory was based on findings from separate studies. An early study in input device performance found a homing time of roughly 400 ms from the *keyboard to the mouse* (Card et al., 1978). At that time, it was thought that homing times to the keyboard and to the mouse were identical. Since then, the Douglas study found a higher homing time (roughly 700 ms) than that found previously, and attributed it to homing time asymmetry (Douglas and Mithal, 1994).

The workstation thoughput portion of this study is the first to measure both to-keyboard and to-mouse homing times in the same set of experiments. While homing times were found to be higher overall than those of the previous studies (with a to-mouse homing time of ~650 ms, and a to-Command Chair pointer homing time of ~130 ms as compared to to-keyboard homing times of roughly 1000 ms), the same asymmetry of roughly 300 ms persisted. As previously mentioned, the most likely reason for the increased to-keyboard homing time is that more precision is required to place the fingers on the keyboard "home row" than is required to grasp the mouse.

In addition to throughput measurements, the efficiency metric of accuracy can be measured by comparing device error rates. In this experiment, the error rate of the Command Chair was measured to be roughly double the error rate of the other tested workstation configurations. This finding is in line with the time performance measurements, since more difficult pointing leads to both reduced accuracy and increased error rates.

In addition to input difficulties, another variable likely affected the accuracy and speed results. The "viewing distance," (distance from the user's eyes to the viewing screen) varied between workstation configurations – representing a potentially confounding uncontrolled factor. This occurred because the traditional keyboard and mouse arrangement sit on the desktop, whereas the Command Chair armatures must sit in front of the desktop (or else the armatures and desk collide). As a result of this, users had to sit further from the monitor with the Command Chair relative to the other workstation configurations – leading to an increase in viewing distance of roughly 11". This increased viewing distance likely increased the difficulty of accurate pointing by artificially reducing making the targets more difficult to see (potentially reducing their effective size). Therefore, increased viewing distance likely artificially decreased the pointing performance of the Command Chair.

4.4.2 *Intuitive Input*

Quantitative measures of performance improvement over time (relating to learning and intuitive input) were similar for all three workstation configurations. The qualitative questionnaire supported this finding, as 11 of the 12 test participants responded that the Command Chair was "easy to learn." These findings support the claim that the Command Chair is an intuitive device to use. Intuitive use was facilitated by maintaining a natural mapping of input motion to output motion for the Command Chair.

Relating to intuitive input, the positive learning results found in this study were somewhat contradicted by some of the other subjective findings. In particular, users felt that the Command Chair required more "mental effort" than the other workstation configurations. Similarly, users found that the "ease of use" was diminished with the Command Chair. However, these responses are not surprising considering that all of the users were experts using the traditional workstation setups, and complete novices using the Command Chair. So, these results are not that daunting. Additionally, some of these comments partially relate to frustration with performance issues in achieving the desired outcome, rather than difficulties in understanding how to obtain the desired outcome.

Learning for typing was not considered in this experiment. However, observations and user comments indicate that learning was required for good typing performance. The Command Chair typing performance likely partially reflects users' unfamiliarity with the system. So, other forms of learning beyond pointing appear to play a role in the evaluation of workstation performance.

4.4.3 Device Comfort

The findings of wrist position analysis confirm that the design of the Command Chair was successful in improving wrist posture, and reducing wrist motion. Even though radial deviation was found to be somewhat worse with the Command Chair, this effect can simply be corrected by a slight design modification — due to the excellent wrist posture control that the Command Chair provides (shown by the low wrist posture standard deviation). Corresponding with these findings, users felt significantly less wrist fatigue after using the Command Chair relative to using the other input stations.

The short answer questions verified some of the overall comfort benefits of the Command Chair – with 8 of the 12 users feeling that the Command Chair was comfortable to use. Additionally, 7 of the users commented that they liked the comfort or reduced fatigue associated with the Command Chair. The rating on the Visual Analog Scale of "overall comfort" showed a trending (though not yet statistically significant) preference to the Command Chair over a traditional workstation configuration.

The smallest study participants experienced less comfort with the Command Chair than other participants. As previously mentioned, the two subjects 5'2" in height were much more critical of the Command Chair comfort relative to the other participants. It appeared that the size of the Command Chair was simply too large for these subjects to comfortably use, thereby providing less comfortable reaching distances and postures. User feedback on comfort from the other ten study participants was much more positive. For this reason, future versions of the Command Chair should be better suited for smaller users – either through providing various sizes of device, or by providing more system adjustability (particularly the reach from the palm rest to the keyboard, and the distance between the system arms).

4.4.4 Most Promising Command Chair Applications

Based on participant feedback, observations of the Command Chair in use, and the preceding evaluation of the performance of the Command Chair, it appears that the Command Chair would be most beneficial for users who perform many combined tasks (requiring repeated device switching), and users most susceptible to wrist injuries. Note that these recommendations are based solely on the performance characteristics discussed in this chapter, and are not influenced by the benefits of bimanual input that the Command Chair also provides.

Considering typical work requirements, users have suggested that the Command Chair would be most useful for spreadsheet and database types of applications. This is because these applications require repeated switching between pointing and keying input devices. Users also suggested that the Command Chair would be well suited to a variety of video games – many of which require constant pointer motion input while simultaneously requiring commands to be issued from the keyboard.

From a comfort standpoint, the Command Chair was designed to provide many benefits. In addition to forearm support (also provided by the *Morency*™ rest), the benefit highlighted by this series of experiments was the improvement of wrist posture, and a reduction in wrist motion. This finding suggests that people currently suffering from wrist injuries, or who are prone to wrist injuries, would likely benefit the most from the Command Chair. Of course, use of the Command Chair would also likely assist in injury prevention for the general populace, as well. Future analyses of other ergonomic benefits of the Command Chair will likely expand the list of potential beneficiaries.

4.5: Chapter Conclusions

1) The Command Chair showed much greater control of wrist position relative to a mouse and keyboard workstation or a workstation with fixed forearm support. This control was shown in reduced wrist posture standard error.
2) Wrist extension, a risk factor for Musculoskeletal Disorders was significantly reduced with the presence of forearm support.
3) Subjective measures reinforced the findings of the quantitative analysis. In particular, subjects noticed the Command Chair shift the fatigue from the wrist to the shoulder, as well as its reduced pointing and typing performance.
4) Reinforcing the overall benefits of the Command Chair, five of the twelve subjects stated that they would prefer to use the Command Chair with their own workstations.
5) For throughput (a combined metric of pointing speed and accuracy), the Command Chair demonstrated reduced pointing performance of 42% relative to a traditional workstation configuration. Command Chair performance was roughly equivalent to the pointing performance of a conventional joystick.
6) Typing times for the Command Chair were roughly double those for traditional keyboard typing. This result is likely caused by a combination of lack of experience typing on the Command Chair, the dramatic split of the keyboard, the poor key tactile feedback, and the mobile typing platform.

7) Error rates were higher for both typing and pointing with the Command Chair.
8) Providing fixed forearm support does not affect the pointing or typing performance of a traditional mouse and keyboard workstation configuration.
9) Homing time from the keyboard to the mouse was reduced by an order of magnitude by the Command Chair. However, homing time from the mouse to the keyboard remained unchanged relative to other workstation configurations.
10) Learning rates were similar for all three workstation configurations.

Chapter 5: Analysis of the Tradeoffs between Efficiency and Comfort in Computer Input

5.1 Introduction

The pointing speed of the mouse has been found to be very close to the pointing speed of the unencumbered human hand – meaning that it is almost impossible for other input devices to surpass its speed (Card et al., 1978). Additional studies have found few input devices capable of even matching the input speed of the mouse (MacKenzie et al., 1991, Zhai et al., 1997).

Unfortunately, this means that new ergonomic input devices will most likely have lower input efficiency than the mouse – today's standard pointing device. This has been shown for several pointing devices intended to improve input comfort. For instance, the *Renaissance*™ mouse was shown to demonstrate significantly improved comfort over a traditional mouse, but roughly 10% slower input speed (Aaras, et al., 1999). Another example is the "neutral mouse," which was shown to improve posture and reduce loading, but was roughly 24% slower than a traditional mouse (Gustafsson and Hagberg, 2003). Similarly, chapter 4 showed that despite its comfort advantages, the Command Chair demonstrates lower input efficiency than the mouse.

Conflicting findings across disparate measures of input performance makes comparing overall input device performance very difficult. This problem not only affects designers, who have difficulty in discerning which dimensions are the most important for overall input device performance, but also consumers, who have a difficult time deciding which input device is “better” for their own use to justify a purchase. This chapter will address this problem by presenting a cost basis for normalizing dissimilar measures of input performance, with an emphasis on efficiency and comfort.

5.2 Cost Basis for Input Device Performance Comparison

Considering each input performance dimension on a monetary level provides a basis for comparing each of the performance dimensions in the same units. In turn, this allows each performance component’s contribution to the overall device performance to be considered and understood. Simply put, the cost basis allows for an apples-to-apples comparison of performance measures that are not normally measured on the same scale. Of course, some work must be done to make the conversion from traditional performance measures to monetary costs.

5.2.1 Costs of Throughput per Equivalent Day’s Work

In order to normalize efficiency to cost, the costs associated with generating an equivalent amount of work between workstations must be considered. To do this, the throughputs of the systems must be considered (serving as the measure of efficiency). If only pointing tasks are being considered in the cost comparison, throughput values as defined by Fitts’ tapping tests may be used.

However, a broader definition of “throughput” is also applicable in this case – the amount of computer work performed in a given amount of time. This throughput equals the inverse of the time required to perform a unit of work. A “unit of work” is an arbitrary measure of work, which must remain consistent between the workstations being compared. As in the pointing example, it could represent “one bit” of pointing information. Or, it could represent a more complex task, such as the combined pointing and typing task presented in the previous chapter.

Using throughput measurements, and an arbitrary reference workstation, the number of tasks that the reference workstation can perform in a day's work can be calculated using Equation 1. All other comparison workstation's labor requirements are adjusted in order to provide this same amount of reference work in a given day. $Time_{computer}$ represents the number of hours spent on the computer by the workers. The labor cost required to perform a single task for a given workstation is given by Equation 2.

$$1)\quad \frac{Tasks_{reference}}{day} = Throughput_{reference}\left(\frac{tasks}{\sec}\right) * \frac{time_{computer}}{day}$$

$$2)\quad Throughput\ Cost\,(\$) = \frac{LaborCost\ (\$)}{time\,(\sec)} * \frac{1}{Throughput_{\ comparison}\ \left(\frac{tasks}{\sec}\right)} *\#\,tasks$$

Plugging Equation 1 into Equation 2 gives the cost per day to generate a fixed amount of work defined by the reference workstation's performance. This is the desired outcome – the cost of throughput per equivalent day's work, which can be calculated for each workstation configuration under consideration. The results of these calculations are the work normalized labor costs.

$$3)\quad \frac{ThroughputCost(\$)}{day} = \frac{LaborCost(\$)}{time(\sec)} * \frac{Throughput_{reference}\left(\frac{tasks}{\sec}\right)}{Throughput_{comparison}\left(\frac{tasks}{\sec}\right)} * \frac{time_{computer}}{day}$$

Labor costs are set by industry, and can be found from the Bureau of Labor Statistics (BLS) for a given job. The average labor cost for a white collar worker is \$19.86 per hour. Similarly, average computer use ($time_{computer}$) for a worker is estimated at roughly 4 hours per day. This value may be adjusted for a specific job or application being considered for a new workstation configuration.

Learning costs (relating to the costs of non-intuitive input) can also be incorporated by including them as a non-linear factor in throughput as a function of time. However, as learning rates were found to be similar for the Command Chair and the mouse in Chapter 4, they were not included in the analysis presented in section 5.3.

5.2.2 Injury Costs

The costs associated with comfort most directly manifest in the costs associated with work-related Musculoskeletal Disorders. As noted in Chapter 1, these costs can be very high. The most significant costs associated with these sorts of injuries include the cost of worker's compensation claims, as well as the number of workdays lost per injury. Lost workdays are multiplied by the labor rate to generate the monetary cost of paying a replacement employee to make up the lost work of the injured employee. Note, however, that there are other costs associated with these injuries that are more difficult to quantify, such as pain and reduced worker efficiency. For example, work injuries have been shown to reduce worker productivity (Hagberg et al., 2002), but to an unknown degree.

In addition to these costs, the key pieces of information that are required to convert injury to monetary costs are average worker injury rate and workstation risk factor hazard ratios. Fortunately, both of these pieces of information have been provided by a recent study which tracked injury incidence among 632 workers over a period of three years and correlated injury risk with computer workstation configuration. The results of this study have been reported in a pair of publications released by the joint research team. Gerr et al. (2002) reported on the injury rates of employees over time, whereas Marcus et al. (2002) reported the hazard ratios associated with injury risk for a variety of workstation configurations.

Figure 5.2.1 shows the injury incidence among study participants as a function of time per 100 workers. Injury rates were differentiated between "hand and arm" injuries, and "neck and shoulder" injuries. Note that these values represent injury incidence, and not the number of injured workers, since some workers suffered multiple injuries. These graphs present the combined injury rates for all workstation configurations, and therefore represent the average injury rate.

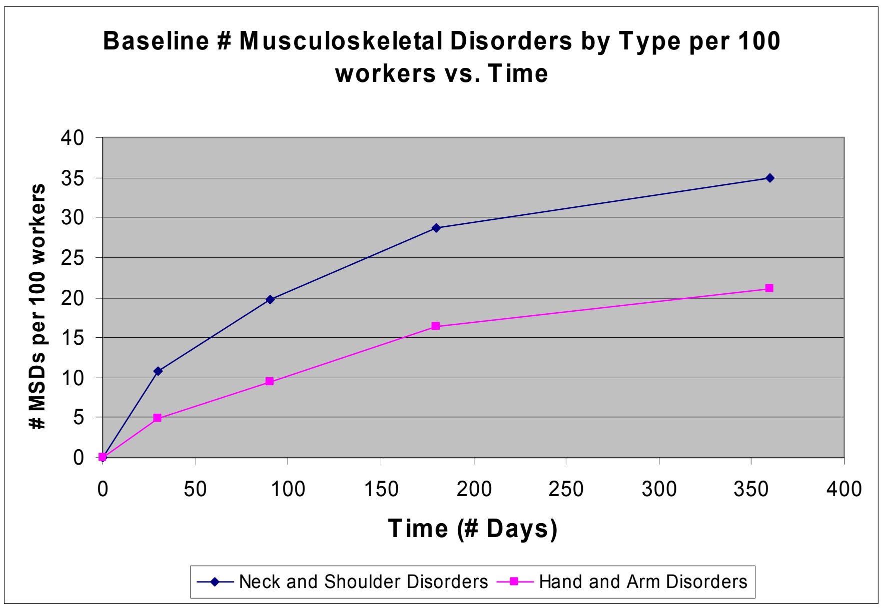


Figure 5.2.1: Measured Injury Rate of a Conventional Workstation over Time
(data from Gerr et al., 2002)

With this information in hand, the only additional information required to calculate the complete workstation cost as a function of time is the injury risk of each workstation configuration. As previously mentioned, this information can be obtained by looking at the predictive hazard ratios relating to injury risk provided by Marcus et al., (2002). These hazard ratios were measured for only *specific* workstation configurations, so the *average* hazard ratio must first be interpolated for each postural risk factor. This was calculated for this study using a simple averaging function (Equation 4) using the given hazard ratio levels, and the number of subjects measured in each workstation configuration ($n_{subjects}$).

4) $$HazardRatio_{average} = \sum number_{samples} * HazardRatio \Big/ Number_{total}$$

Once the average hazard ratio was found for each category, the adjusted hazard ratio for the comparison workstation configuration was calculated. This was done by normalizing the specific postural risk factor hazard ratio to the average workstation hazard ratio. This took two steps (Equations 5a and 5b). First, the percentage difference of the specific hazard ratio to the average hazard ratio was calculated. Next, this percentage was subtracted from one hundred percent in order to make the calculated percent difference from the average represent the overall injury risk.

5a) $$HazardRatio_{percentage} = (HazardRatio_{average} - HazardRatio_{specific}) \Big/ HazardRatio_{average}$$

5b) $$HazardRatio_{normalized} = 100\% - HazardRatio_{percentage}$$

Once these values have been obtained for each of the specific postural risk factor differences, the normalized hazard ratios are multiplied together to obtain the final injury risk modifier. The injury risk modifiers represent the injury risk percentage based on all of the postural differences between the workstations. Two separate final injury risk modifiers must be calculated – one each for hand and arm (H/A) injury risk, and another for neck and shoulder (N/S) injury risk. These values are multiplied by the average number of injuries as a function of time as plotted in Figure 5.2.1 to generate the number of expected injuries as a function of time for that workstation configuration. Predicted hand and arm injuries are then added to the predicted number of neck and shoulder injuries to obtain to the total number of predicted injuries. The number of predicted injuries is then multiplied by the injury cost per injury (shown in Table 5.3.1) to generate the injury cost as a function of time associated with that workstation. This calculation is shown in Equation 6.

$$6)\ \frac{InjuryCost(\$)}{day} = (HR_{normalized(H\&A)} * \frac{InjuryRate(H\&A)}{day} + HR_{normalized(N\&S)} * \frac{InjuryRate(N\&S)}{day}) * \frac{InjuryCost(\$)}{injury}$$

	Cost	Description	Reference
Labor Costs	$19.86/hr.	White Collar Labor Rate	BLS - 2003
	4 hours/day	Average Computer Use/day	Typical value – but application and job dependent
Injury Costs	$38,500	Workers Comp. Cost per Upper Extremity MSD Injury Claim	CA CHSWC - 2000
	12 days	Workdays lost per injury	BLS - 2000
Fixed Costs	$400	Typical Workstation Cost	
	$1000	Estimated Command Chair Cost	

Table 5.2.1: Labor, Injury, and Fixed Costs Associated with Computer Input

Table 5.2.1 shows the current publicly available cost data that is required for these calculations. These are the values that are used for the cost comparison of the Command Chair in section 5.3. However, when performing this analysis, the best available data specific to the job being considered should be used instead.

One of the main assumptions made in using the numbers presented here is that the Musculoskeletal Disorders (MSD) reported by Gerr et al. generated treatment costs equivalent on average to the average Worker's Compensation cost per upper extremity MSD as reported in 2000 by the California Commission on Health, Safety and Workers Compensation (CHSWC). This assumption is necessary as Gerr did not provide the treatment costs required for the injuries he measured. However, it is possible that the two sources of information could refer to injuries of differing severities. Section 5.3 presents a brief sensitivity analysis to examine the effects that potential inaccuracies in these cost numbers may cause in the final comparison analysis.

5.2.3 Fixed Costs

Fixed costs must also be considered in the cost basis workstation comparison. In this case, the fixed costs represent the purchase costs for the workstations being compared. The fixed costs for workstations are often low relative to operating costs, and therefore typically contribute little to the overall cost of operating the workstation.

Like the "cost of throughput per unit work," these fixed costs must be normalized to a unit of work. This is because a workstation with inferior performance will not only require more labor to achieve that unit of work, but also more workstations to accommodate that labor. For this reason, the same normalization must occur for the fixed costs as for the throughput values. This normalization is shown in Equation 7.

7) $$Cost_{Workstatio\,n,Normalized}(\$) = Cost_{Workstatio\,n,purchase}(\$) * \frac{Throughput_{reference}(\frac{tasks}{\sec})}{Throughput_{comparison}(\frac{tasks}{\sec})}$$

5.2.4 Total Costs

Once the variable costs for throughput and injury rate have been calculated, these can be added to the fixed costs to obtain a total monetary cost of operation as a function of time, as shown in Equation 8. These costs are calculated for all of the workstations being considered.

8) $$Cost_{total}(\$) = (\frac{InjuryCost(\$)}{day} + \frac{ThroughputCost(\$)}{day}) * time(days) + Cost_{Workstation,Normalized}$$

With the costs associated with all of the considered workstations in hand, comparisons of the workstations are simple. Two cost scenarios exist. The first possibility is that one of the workstations is cheaper to operate under all conditions.

Since the ultimate goal is to minimize cost, the cheaper workstation would be selected for purchase. The other possibility is that the costs intersect each other when plotted versus time. In this case, the breakeven cost would need to be calculated, and the period of workstation use would need to be considered. The workstation that was cheaper over the anticipated period of use (e.g. the lifetime of the workstation) would then be selected.

5.3 Cost Basis Comparison of the Command Chair to a Traditional Workstation

5.3.1 Generating Workstation Operating Costs

Using this technique, the costs associated with the Command Chair were evaluated with respect to the traditional workstation using a separate chair, keyboard and mouse. The throughput values for these workstations were derived from the workstation throughput experiment discussed in Chapter 4. These results were selected to represent combined typing, pointing, and homing performance of the workstations under consideration – a more complete representation of workstation performance. The Command Chair required 6.12 seconds to complete an average trial of the combined pointing, typing, and homing test. The inverse of this (.243 trials/second) represents the throughput of the Command Chair used for the cost comparison. Similarly, the mouse and keyboard required 4.21 seconds to complete a trial of the same test. This corresponds to a throughput of .163 trials/second. These values, combined with those of Table 5.2.1 provide all of the information required to calculate the throughput cost per day's work as shown in Equation 3. Similarly, these values are sufficient to calculate the normalized workstation cost given in Equation 7.

These throughput costs, along with some other relevant values are presented in Table 5.3.1. Note that "injury cost per injury" is calculated by adding the "worker"s compensation cost per injury" to the product of the "number of days lost per injury" and the "daily labor rate." Note also the assumptions behind these numbers stated in section 5.2.

Parameters	**Values**	
Labor Rate / hour	$19.86/hr.	
hours on computer /day	4 hours	
Computer Labor rate/day ($/day)	$79.44/day	
Injured labor rate/day ($/8-hour day)	$158.88/day	
# days lost/injury	12 days	
Worker's comp cost/RSI claim ($)	$38540.00 / claim	
Injury Cost per injury	$40449.56 / injury	
	Keyboard/Chair/Mouse	**Command Chair**
# injuries over time	.011507*(time)^.7057 - 1	.0108*(time)^.6121 - 1
Throughput (info/s)	0.243	0.163
Workstation Purchase Price	$400	$1000
Normalized Workstation Cost	$400	$1491
Throughput Cost/Day's Computer Work	79.44	118.43

Table 5.3.1: Cost Comparison Constants of Command Chair vs. Traditional Workstation

Given this information, the final step in the cost comparison is to compute the number of estimated injuries for the Command Chair and calculate injury cost as a function of time. Recalling Chapter 3, some of the injury risk factors addressed by the Command Chair that were included in the Marcus study are: keyboard inner angle greater than 121 degrees, forearm support, no wrist rest (wrist pressure), neutral wrist position, and distance of table edge to "j" key >12cm. Table 5.3.2 shows the corresponding risk factor hazard ratios for each of these postural risk factors normalized to an average workstation, as calculated from the data provided by the Marcus et al. study (2002).

	Postural Risk Factor	Command Chair Level	Adjusted Hazard Ratio
Neck/Shoulder Disorder Risk Factors	Presence of Chair Armrest	Yes	.89
	Keyboard Inner Elbow Angle	>121°	.49
Hand/Arm Disorder Risk Factors	Distance from table edge to ‘j’ key	>12cm	.68
	Mouse Ulnar Deviation Angle	0° *	.79
	Presence of wrist rest	No	.90

* - after modification

Table 5.3.2: Postural Risk Factor Hazard Ratios Normalized to Average

Applying these risk factors and multiplying them by the average workstation injury rate generates the total number of predicted injuries for the Command Chair over time, as plotted in Figure 5.3.1. The total number of injuries of the typical workstation configuration as measured by the Gerr study is charted for comparison. As can be seen from this figure, the risk factors that the Command Chair addresses reduce the predicted number of injuries by roughly half. To find values of injury rate between the four values provided by Gerr at different time intervals, power curves were fit to the measured and predicted injury rates. The equations for these curve fits are presented in Table 5.3.1. These curves have a very high degree of correlation with the given data ($R^2 > .98$ for both curves). However, these curves should not be used to predict injuries beyond one year (the final data point presented by Gerr).

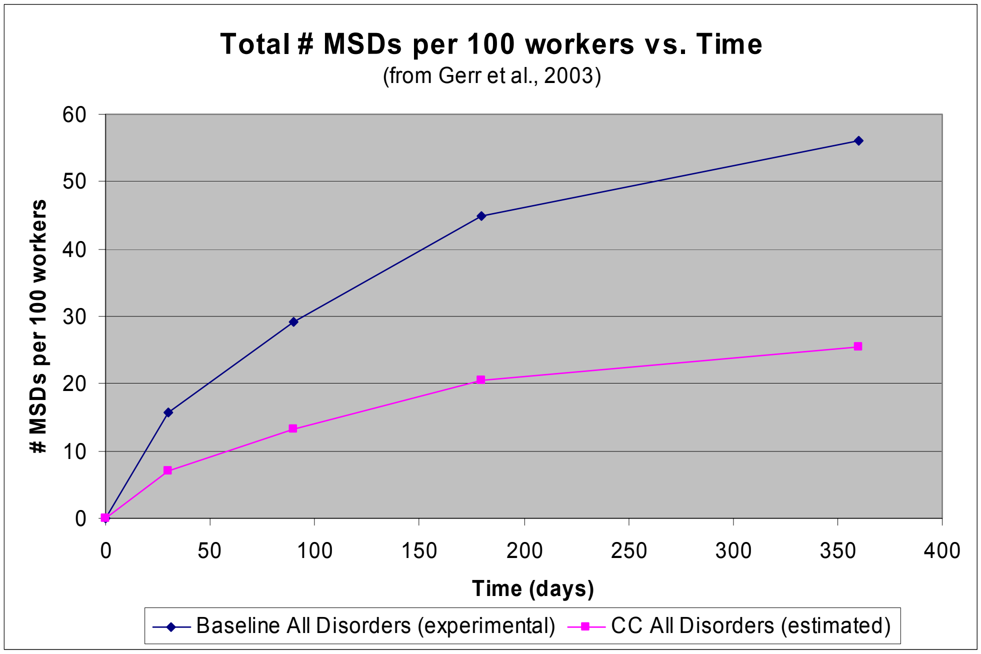


Figure 5.3.1: Injury Rate as a Function of Time

With the predicted injury rate as a function of time, all of the data is available to generate the cost basis comparison of the two workstations. Using Equation 8, the workstation costs were computed for each workstation. Costs were calculated at a variety of times in order to give an idea of cost performance over time. This information is plotted in Figure 5.3.2 as a function of time.

5.3.2 Comparing Total Workstation Operating Costs

As can be seen in Figure 5.3.2, this analysis reveals the cost comparison case where the workstation costs cross over each other. The point at which the cost curves cross over each other, the "breakeven" point, occurs at 34 days. After this point, the Command Chair is projected to be less costly to operate (albeit by only a few thousand dollars over the course of the year). This finding supports the claim that the Command Chair is a better overall computer input workstation than the traditional mouse & keyboard workstation configuration.

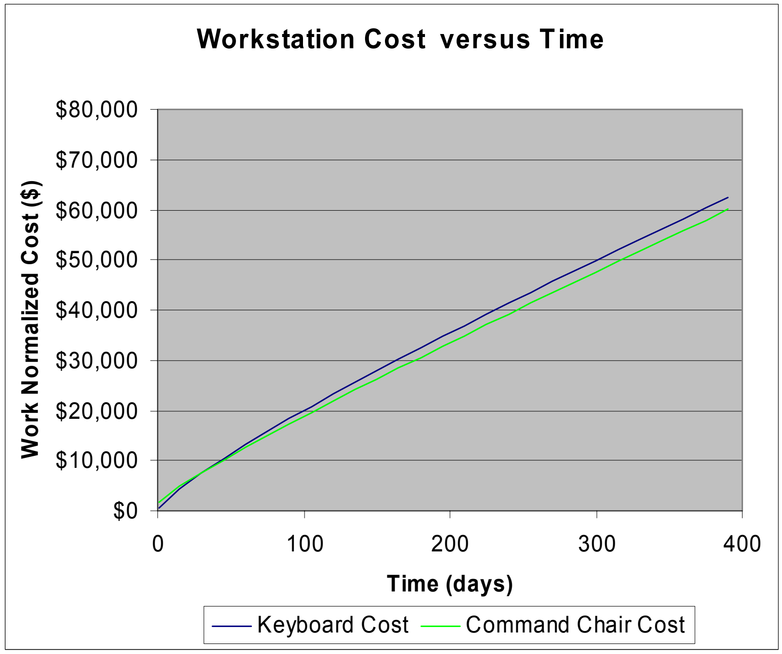


Figure 5.3.2: Work Normalized Workstation Costs over Time

The reason for this crossover point is that the Command Chair has a higher cost up-front (due to the higher purchase cost), but a less steep slope due to its lower predicted injury rate. It is interesting to note that the workstation purchase costs (fixed costs) become insignificant very rapidly relative to the throughput and injury variable costs. Purchase cost represents only 10% of the total operating cost of the traditional keyboard and mouse workstation after only 15 days (and diminishes from there).

Figure 5.3.3 compares the contribution to costs associated with throughput and injury as a function of time for both the Command Chair and the traditional mouse/keyboard/chair workstation. The mouse/keyboard throughput and injury costs are roughly equal over the course of the year. In contrast the linear throughput cost of the Command Chair dominates the injury cost.

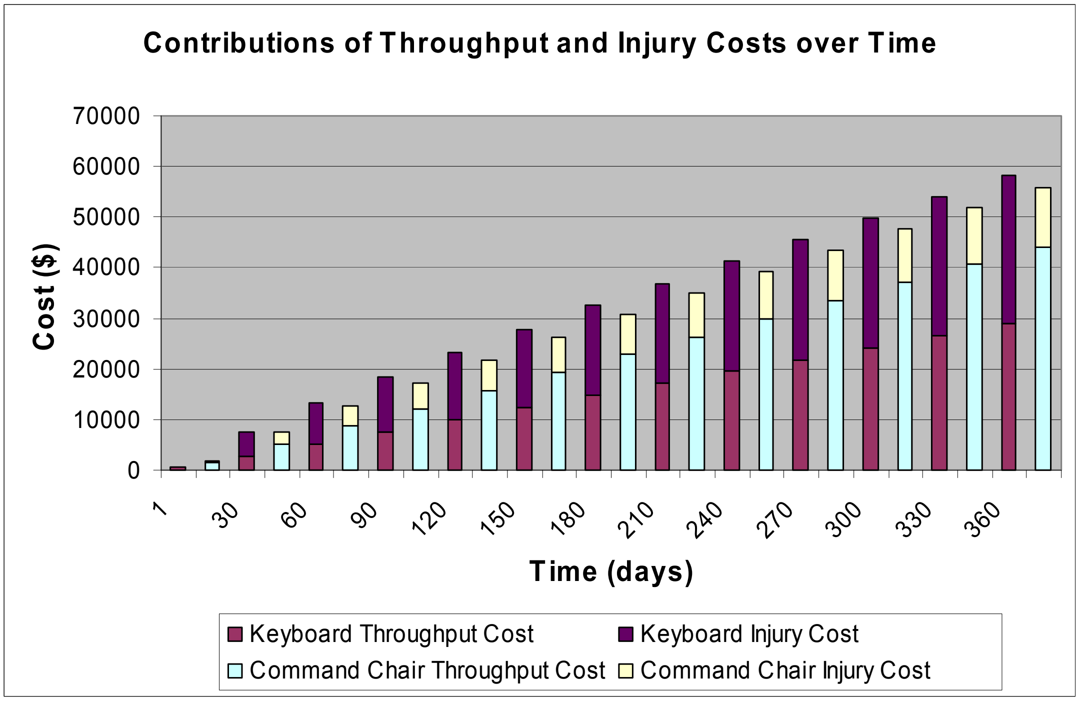


Figure 5.3.3: Comparison of Workstation Throughput and Injury Costs over Time

5.3.3 Sensitivity Analysis

A sensitivity analysis was performed on the primary cost contributing factors to determine which factors have the most influence on the final result. This is important as it reveals both which parameters should be targeted for improving workstation performance, as well as showing how measurement errors may affect the results.

For this sensitivity analysis the following variables were considered: Command Chair throughput, worker's compensation cost, hourly labor rate, and hours of computer use per day. These variables were perturbed by fifty percent and the effects of these changes on total work normalized workstation costs were examined.

The results show that the throughput has the greatest effect on the workstation cost of the Command Chair (a change of roughly 26%), followed by workers compensation costs (a change of roughly 15%). Hourly labor rate and hours of computer use both had a small (and roughly equal amount of 10%) effect on total workstation costs. Injury rate changes have a similar affect to workers compensation costs, as they both affect overall injury costs.

This is good news for the Command Chair because, as discussed in Chapter 4, several ideas exist for improving the Command Chair throughput. If these changes are effective, they will have a dramatic effect in reducing the operating cost of the Command Chair. This will increase the demonstrable overall benefit that the Command Chair provides relative to a traditional keyboard and mouse workstation.

5.4 Breakeven Injury Cost per Injury (Alternative Comparison)

In the event that the Injury Cost per Injury is not well known, an alternative analysis can be performed to help guide a purchase or design decision. To perform this analysis, the total operating costs for each workstation are considered (recalling Equation 8), and are set equal to each other to signify the "breakeven" cost where both workstations demonstrate the same total operation cost. All of the known constants are then plugged into the equations, solving for the breakeven injury cost per injury. Doing this yields Equation 9, as written for the Command Chair and traditional workstation. In the general case, Command Chair costs should be interpreted as the workstation configuration that demonstrates a lower injury rate.

$$9)\ \frac{BreakevenCost(\$)}{injury} = \frac{[(Cost_{CC,Normalized} - Cost_{Key,Normalized}) + (\frac{ThroughputCost(\$)_{CC}}{day} - \frac{ThroughputCost(\$)_{Key}}{day}) * time(days)]}{(\#injuries(time)_{key} - \#injuries(time)_{CC})}$$

Plugging the numbers from Table 5.3.1 into this equation a different points in time (accounting for the fact that #injuries is a function of time) yields Figure 5.4.1 – the breakeven injury cost plotted as a function of time.

To interpret this graph, or the analysis results, first select the amount of time that a workstation is expected to be in service (noting that injury data is only currently valid to one year without extrapolation) to generate the predicted injury rate, then consider the breakeven injury cost. If the expected injury cost is expected to be lower than the calculated breakeven cost, than the traditional workstation (with the higher injury rate) will be cheaper to operate. Conversely, if the expected injury cost is expected to be higher than the calculated breakeven cost, than the Command Chair (or, the workstation with the lower injury rate) will be cheaper to operate.

In the case of this specific analysis, the calculated injury cost from existing data is higher than the breakeven cost after roughly 30 days. This restates the findings of Figure 5.3.2 – the Command Chair will be cheaper to operate if used beyond this period. The advantage of this approach is that it doesn't presuppose the actual injury cost. Instead, it presents a range of possible costs for which either device may be more beneficial.

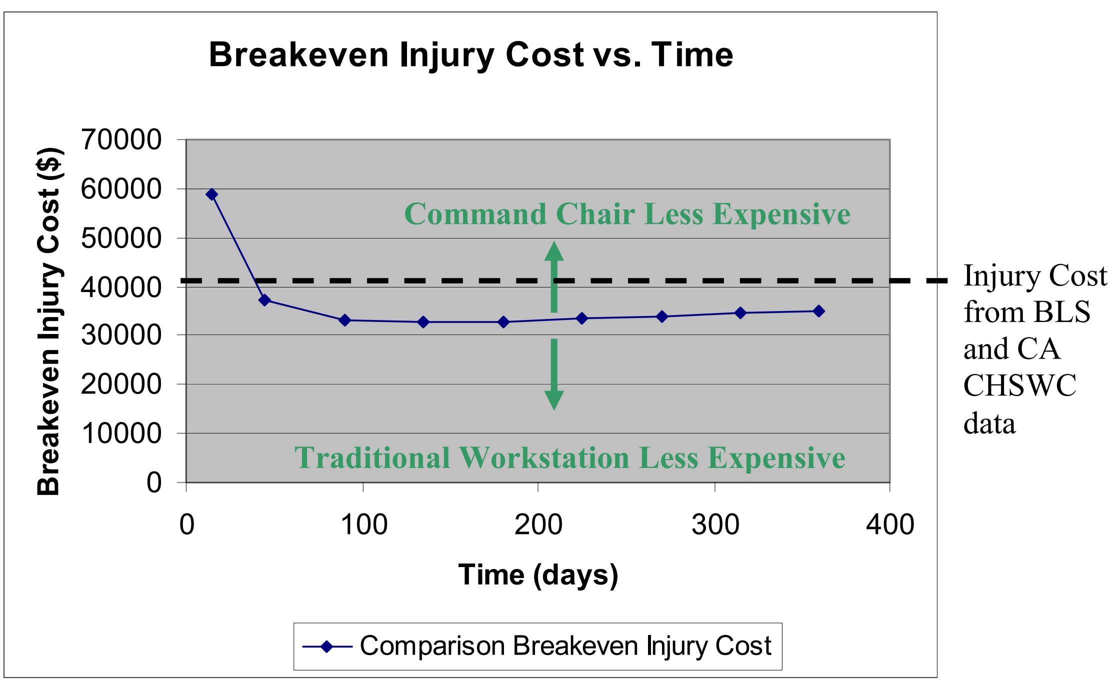


Figure 5.4.1: Breakeven Injury Cost versus Time

5.5 Chapter Conclusions

1) A new technique to normalize the various performance metrics of computer workstations to monetary cost has been developed. This technique allows for simple comparisons between workstation configurations that display strengths in different performance dimensions (e.g. input speed versus comfort). Previously, workstations could only be compared within specific categories, and overall workstation evaluations that considered the tradeoffs between these categories were not possible.

2) Using this technique, the Command Chair was found to be less costly to operate than a traditional keyboard and mouse workstation if the workstation is to be used for more than 34 days. This finding supports the claim that the Command Chair is a better overall computer input workstation than the traditional mouse and keyboard computer workstation.

Chapter 6: Bimanual Computer Input – A New Technique and its Comparison with Existing Techniques

6.1 Introduction

In addition to the physical input properties that the Command Chair provides, it also provides pointing input from both hands. Unfortunately, this benefit is not utilized in today's standard computer interfaces, which make use of only one pointing device. To take advantage of this Command Chair capability, new software and input techniques must be developed to make meaningful use of two-handed physical input. Exploring methods for making meaningful and beneficial use of the bimanual (or, two-handed) input of the type that the Command Chair provides will be the focus of this chapter.

People naturally use two hands when performing physical operations, indicating that two-handed manipulations are a natural mode of interaction for humans. Prior research in bimanual interfaces has shown that the presence of pointing devices in both hands can lead to more natural interaction. Focusing on the metrics of greatest interest:

Bimanual interfaces can improve **intuitiveness** by:

- *Enabling more input methods* – allowing the body to make virtual manipulations that more closely match physical manipulations.
- *Enabling more sensory feedback* – such as utilizing body awareness (proprioception).

Bimanual interfaces can improve **efficiency** by:

- *Facilitating parallel input* – enabling multiple simultaneous input streams, thereby reducing overall input time.

Bimanual interfaces can improve **comfort** by:

- *Splitting workloads between two limbs* – reducing the load on a single limb.
- *Providing new body positions and motions* – potentially providing more comfortable input.

Taking advantage of these potential benefits requires careful interface design. Previous studies have shown that poorly designed bimanual interfaces can be inferior to standard one-handed interfaces (Kabbash et al., 1994, Kurtenbach et al., 1993). This chapter presents a new bimanual input technique called "Bimanual Marking Menus," and builds on previous work by comparing traditional and new techniques not previously evaluated together. These techniques include:

- *One-handed techniques*

  Standard toolbars and Marking Menus
- *Keyboard/Pointer bimanual techniques*

  Mapped Hotkeys and Grouped Hotkeys
- *Dual pointing device bimanual techniques*

  Toolglasses and Bimanual Marking Menus

Bimanual marking menus represent a new bimanual input technique that allows users to manipulate objects with one hand while, in parallel, issuing commands with the other. The study compares the six techniques above in the context of a simple shape drawing task. This task was chosen for its similarity to relevant and commonly encountered tasks. The approach of this study follows the lead of and builds upon previous explorations into bimanual input.

6.2 Review of Previous Work

Buxton and Myers (1986) were among the first to demonstrate the potential of bimanual input. They found that experts using their system performed a navigation and selection task 15% faster than experts using a similar one-handed system. Further, they found that as the percentage of parallel activity (*i.e.*, the time that both hands were moving simultaneously) increased, input speed also increased. Subjects were also able to quickly understand the new interface, enabling novices to perform as well as experts of the traditional interface. Recent research has explored bimanual interfaces in other contexts.

6.2.1 Bimanual Interface Metaphors

Interface metaphors can guide the design of virtual interfaces that more closely map to physical manipulations. The pointer is so well established that few designers pause to think of the interface metaphors it uses. Metaphors for bimanual interfaces, however, are still evolving. This section describes commonly used bimanual metaphors.

Independent hands

A common metaphor treats the pointer as the user's hand, capable of pointing at and "touching" objects on the screen. Thus, a simple bimanual interface metaphor might treat a pair of pointers as two independent hands. This approach fully enables parallel input, while maintaining maximum versatility for each hand. However, a study by Kabbash, et al. (1994) demonstrated that two completely independent cursors can lead to reduced performance. They found that two independent cursors caused the cognitive load of the interface to increase by splitting users' attention between two separate areas of the display.

Nevertheless, independent manipulations show potential in some applications. For example, one area that shows promise is shape editing (Owen et al., 1998). With two-handed "stretchable" shapes, users have much more control of size, form, and position of virtual objects. This can be especially helpful for splines, which have multiple, non-intuitive control handles. This approach has also been extended to 3D volume manipulation using two manipulators with six degrees of freedom (Llamas et al., 2003).

The Kinematic Chain

In 1987, Yves Guiard presented the Kinematic Chain Theory, a theoretical framework regarding the way that humans use their two hands. Presuming the right hand is dominant, the basic tenets of the Kinematic Chain Theory are as follows:

Right-to-left spatial reference **-** the left hand sets the frame of reference for the action of the right hand.

Left-hand precedence in action **-** the sequence of motion should be left followed by right.

Left-Right scale differentiation **-** the granularity of action of the left hand is coarser than the right.

For the general case, "left hand" and "right hand" are changed to "non-dominant hand" (NDH) and "dominant hand," (DH). Guiard performed several experiments to support his theory. For example, Guiard observed that people tend to use their non-dominant hand to position paper during handwriting. He found that handwriting speed was reduced by 20% when users were not allowed to use their non-dominant hand to re-position the paper during writing. In the Kinematic Chain Metaphor, then, the NDH sets the frame of reference for the dominant hand. Several studies since then have supported the benefits of using this metaphor in bimanual interfaces. (Hinkley et al., 1997, Kabbash et al., 1994, Kurtenbach et al. 1997).

Parameter and Command

Another bimanual interface metaphor that has received less attention is that of Parameter/Command. The idea behind this approach is that one hand is used to manipulate parameters, while the other is used for command selection (Brooks, 1995). This is similar to how humans perform many common physical manipulations. While stapling, for example, one hand positions the desired paper stack, while the other hand selects the "staple" operation.

Many aspects of the Parameter/Command metaphor are compatible with that of the Kinematic Chain. In particular, the hand used for command selection can provide a courser motion, and set a frame of reference (in this case, the mode of operation). These approaches have been successfully coupled (*e.g.*, in Toolglass (Bier et al., 1993)).

Also the Parameter/Command metaphor is the basis for the most widely used form of bimanual interfaces: hotkeys. In a recent study (McLoone et al., 2003) both dedicated and chorded hotkeys were found to be faster than the standard pointer/toolbar interface. Since hotkeys provide increased input parallelism and reduce the need for pointer motions, this result is not surprising.

While few studies have explicitly acknowledged the Parameter/Command bimanual metaphor, several have implemented it in command selection experiments (Balakrishnan and Patel, 1998, Dillon et al., 1990, Kabbash et al., 1994) and demonstrated its benefits. As it seems to be one of the less explored avenues for bimanual computer interfaces, this metaphor was selected for further study.

6.2.2 Previous Command Selection Studies

The study presented here roughly follows the pattern set by two previous studies. Dillon et al., 1990 compared toolbar selection speed and error rates when using one mouse as compared with two mice (as well as other command selection techniques). Users selected either a blue line or a red line from a toolbar to perform a connect-the-dots task. The results showed two-handed command selection techniques to be slightly faster than the one-handed technique.

Kabbash et al., 1994, conducted a similar study, but used a trackball in the non-dominant hand and also tested palette and toolglass techniques. The experimental task was very similar to Dillon's, but included four color choices. Two independent cursors were found to be slightly slower than one cursor. The palette was no faster than the standard, one-handed toolbar. But, the two-handed toolglass technique performed about 16% faster than the toolbar.

It is worth noting that many of the benefits of bimanual interfaces come from higher level activities, such as "chunking" commands and parameter selection into a seamless input flow (Buxton, 1986). The benefits of chunking have been well documented (Kurtenbach et al., 1997, Owen et al., 1998) and should be considered in any real-world implementation. As in the studies above, the present study excludes chunking in order to focus on command selection performance only. Still, command selection issues remain very relevant to real-world tasks.

6.3 Method

It is important to note that the study presented here used two mice for input, rather than the Command Chair. This was done in order to decouple the learning effects of the software techniques from the learning effects of the new hardware.

In addition to re-testing the two fastest methods from Kabbash's study: toolbars and toolglasses, the present study also compared marking menus, hotkeys, and bimanual marking menus. The experimental task was a shape drawing task, rather than a connect-the-dots task. This task was selected to imitate common graphics tasks – more commonly encountered and relevant than connect-the-dots.

6.3.1 Shape Drawing Task and Command Selection Techniques

Command selection techniques were compared by requiring subjects to perform a series of shape drawing trials for each technique. Each trial had the following steps:

1. *Pause Screen:* Gave a clear break between trials. A mouse click moved to the homing screen.
2. *Homing Screen:* The dominant cursor automatically homed to screen center, and subjects clicked to continue. This gave experimental control over shape position relative to initial cursor position.
3. *Draw:* Users first selected a desired shape (line, rectangle, or oval) using a predetermined command selection method. Users then drew a matching shape on top of a displayed target shape by specifying the shape's two control points.
4. *Repeat:* Selecting the wrong command or "missing" the target shape recorded an error. Subjects repeated the same trial until successful, but only one error was recorded.

All shapes were drawn by clicking on the initial control point, stretching the shape (with the mouse button depressed) to the second control point, and releasing the mouse button. As shown in Figure 6.3.1, all three of the presented shapes (line, rectangle and oval) required the specification of only two control points to draw the shape. Note that drawing an oval was analogous to drawing a rectangle, but with fewer visual cues for alignment (the dashed bounding box was not displayed). A shape control point target tolerance of 2.4% of the screen size was used for error calculations.

This task simulated disconnected drawing operations similar to those encountered when modifying a diagram with modern graphics software. Unlike the connect-the-dots task, this task does not exploit spatial or temporal locality between operations. Completion time was measured from the disappearance of the homing screen to the mouse release on the correct second control point. If the first attempt to draw a target shape failed, then the trial was recorded as an error, and excluded from timing analysis. No distinction was made between command selection errors and parameter specification errors.

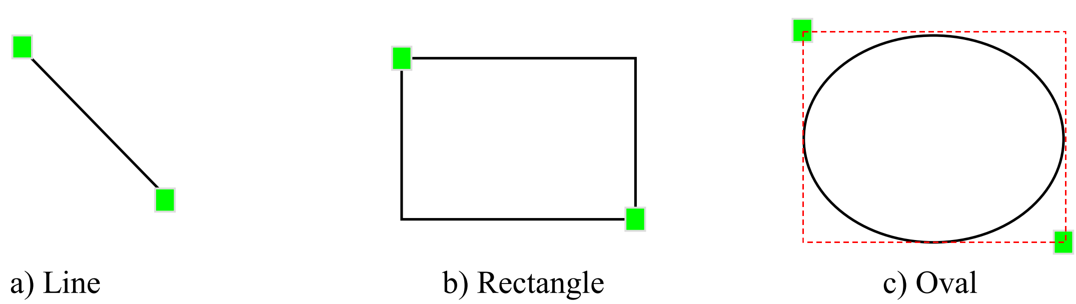


Figure 6.3.1: Two Control Points Fully Specify Shape, Size, and Position for all Three Shapes.

Static Toolbars (TB)

The first input method was the standard mouse and static toolbar interface wherein a single pointer provides all input commands. Using this method, a user moved the pointer from the center of the screen to the static toolbar in the upper-left hand corner of the screen. The user then clicked on the desired shape to draw, and proceeded to draw the shape by clicking on one of the shape's control points, dragging over the shape, and releasing the button to specify the second control point. Since this method is the current standard, it was used as the reference input method.

Hotkeys – Mapped (HKM) and Grouped (HKG)

The second and third methods implemented two flavors of hotkeys: mapped hotkeys and grouped hotkeys. Mapped hotkeys have a cognitive mapping between the key letter and the name of the command that they represent. This mapping may require the user to reposition hands to reach the keys. Key "R" was used to issue the "rectangle" command, "O" for "oval", and "L" for "line."

Grouped hotkeys have no cognitive mapping between the name of the command and the key letter, but are instead grouped so that they can all be reached without the need to reposition the hand. The number keys "1", "2", and "3" were used for lines, rectangles, and ovals respectively. Both hotkey methods required the user to select the command hotkey, while (in parallel) moving the pointer from the homing position to begin drawing.

Toolglass (TG)

The fourth command method was a toolglass previously described in the literature (Bier et al., 1993). Using this method, the non-dominant hand controlled the position of a toolglass (essentially a see-through movable toolbar) in the workspace. The user then clicked *through* the toolglass (with the dominant hand's pointer), simultaneously specifying the command on the toolglass as well as the first control point. The second control point was then specified as usual.

Standard Marking Menus (MM)

The fifth and sixth modes of input both implemented marking menus. Marking menus are a form of pie menus, which pop up in a radial pattern around the cursor when a button is clicked. With marking menus, the menu does not pop up immediately, allowing commands to be issued quickly from memory without the command menu covering the workspace. After 333 ms, the menu pops up to assist users who have not yet memorized the command locations. The name "marking menus" refers to commands leaving a marked trail on the screen, giving the user visual feedback.

The test software issues commands when the command cursor crosses the inner boundary of the pie menu, whether the menu has appeared or not. Since no button click is required, this implementation of marking menus also resembles "control menus" (Pook et al., 2000). A single button on the dominant mouse was used both for menu selection and shape drawing.

The fifth input mode implemented standard one-handed marking menus. Using this method, the user performed command and drawing operations sequentially. First, the user would click anywhere on the screen and select the desired command as described above. Once the desired command was selected, the shape was drawn normally.

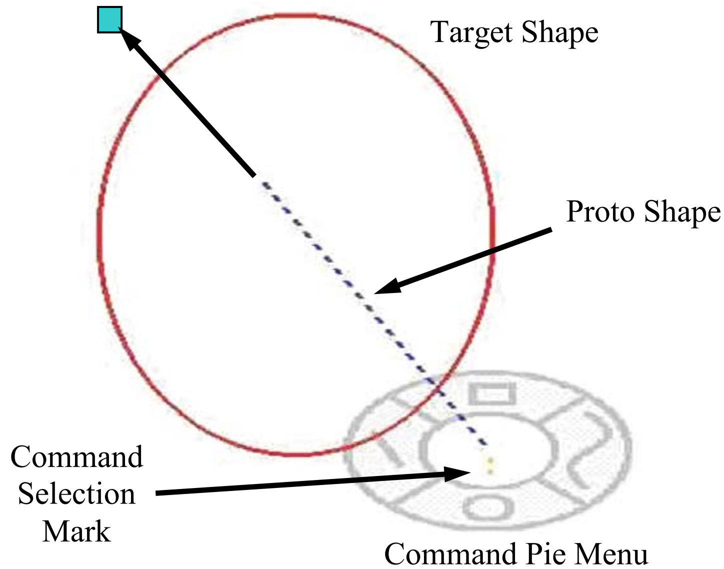


Figure 6.3.2: Drawing and Selecting the Oval Command with Bimanual Marking Menus

Bimanual Marking Menus (BMM)

The sixth mode was an experimental mode following the Parameter/Command metaphor. Bimanual marking menus extend traditional marking menus by allowing the left (or non-dominant) hand to select a command while the right specifies shape control points (not unlike the "marking keys" method (Balakrishnan and Patel, 1998)). To draw a shape, the user first clicks on a shape control point with the right-handed cursor, which causes a pie menu to become active for command selection with the left hand. Like traditional marking menus, the pie menu becomes visible after 333 ms. Once the menu is active, the right hand moves toward the second control point while the left selects the command in parallel, as shown in Figure 6.3.2. There were two motivations for taking this design approach over standard marking menus:

1. Issuing commands and selecting control points could be performed in parallel, rather than sequentially. This was expected to improve overall speed.

2. Following the object-command metaphor, one hand controlled only command selection, while the other specified only control points. Since hands were not required to shift between these operations, it was expected that the interface would be more intuitive.

6.3.2 The Keystroke-Level Model (KLM)

The keystroke-level model represents lowest level of operator detail for the GOMS (**G**oals, **O**bjects, **M**ethods, and **S**election Rules) methodology (Card et al., 1980). It can be used to predict the time an input method requires by reducing it to the basic required operations, along with the associated time for each operation. The fundamental operations that are considered by the KLM are: key or button click (K), pointing (P), homing (H), mental operation (M), drawing (D), and system response (R). Required operation times are then summed to predict the complete method time. These times are provided by the KLM, and are based on a series of experiments that were designed to measure *average* values for each operation (listed in the second column of Table 6.3.2). Heuristics for applying the "mental operation" (M) are shown in Table 6.3.1. Prior to testing the six input methods considered in this study, each method was analyzed using the KLM in order to predict each method's task completion speeds.

Begin with a method encoding that includes all physical operations and response operations. Use Rule 0 to place candidate mental operations (Ms), and then cycle through Rules 1 to 4 for each M to see whether it should be deleted.

Rule 0. Insert Ms in front of all Ks that are not part of argument strings proper (e.g. text strings or numbers). Place Ms in front of all Ps that select commands (not arguments).

Rule 1. If an operator following an M is *fully anticipated* in the operator just previous to M, delete the M (e.g. PMK → PK).

Rule 2. If a string of MKs belong to a *cognitive unit* (e.g., the name of a command), then delete all Ms but the first.

Rule 3. If a K is a *redundant terminator* (e.g., the terminator of a command immediately following the terminator of its argument), then delete the M in front of the K.

Rule 4. If a K *terminates a constant string* (e.g., a command name), then delete the M in front of the K; but if the K terminates a variable string (e.g. an argument string), then keep the M.

Table 6.3.1: Heuristic Rules for Placing the (M)ental Operations (Card et al., 1980)

Operator	Time (sec.)	**Toolbar (TB)**	**Hotkeys Mapped (HKM)**	**Hotkeys Grouped (HKG)**	**Standard Marking Menu (MM)**	**Bimanual Marking Menu (BMM)**	**Toolglass (TG)**
key click - K (.20s)	**0.2**	2	2	1	4	1	1
point - P (1.1s)	**1.1**	2	1	1	1	1	1
home - H (.40s)	**0.4**		1				
mental - M (1.35s)	**1.35**	1	1	1	1	1	2
draw - D (1.37s)	**1.37**	1	1	1	1	1	1
system - R (.33s)	**0.33**				(novices only)	(novices only)	
Predicted Time		**5.32**	**4.62**	**4.02**	**4.62**	**4.02**	**5.37**

Table 6.3.2: KLM Task Completion Predicted Times Summary

Standard Toolbar	
Operation	**Operator**
Point to desired shape command icon	MP
Select icon	K
Point to shape control point	P
Select control point	K
Drag cursor to draw shape	D

Toolglass		
Operation	**Left Hand Operator**	**Right Hand Operator**
Point to shape control point	MP	P
Select control point		MK
Drag cursor to draw shape		D

Standard Marking Menus	
Operation	**Operator**
Click to activate menu	K
Choose Shape Command	M
Boundary Crossing Command	2K
Point to shape control point	P
Select control point	K
Drag cursor to draw shape	D

Bimanual Marking Menus			
LH Operation	**LH**	**RH**	**RH Operation**
		P	Point to shape control point
		K	Select control point
Choose Shape Command	M		
Boundary Crossing Command	2K	D	Drag cursor to draw shape

Hotkeys					
LH Operation	**Mapped**		**Grouped**		**RH Operation**
	LH	**RH**	**LH**	**RH**	
Home hand to hotkey		H			
Choose Shape Command	M		M		Choose Shape Command
Key-in Command	K				
Key-in Command		P	K	P	Point to shape control point
		K		K	Select endpoint
		D		D	Drag cursor to draw shape

Operation Times from Card et al., 1980:
K = .20s, P = 1.1s, H = .40s, M = 1.35s
In this study: **D = 1.37s**

Table 6.3.3: Practiced KLM Task Completion Operation Requirements

Table 6.3.2 shows the number of operations required for each input method, along with the total predicted task completion times. Table 6.3.3 shows the operation sequence used to derive these time predictions. Following the literature, the original KLM method has been slightly modified to account for parallel operations. In the case of parallel operations, the time of the longer operation was used - following the critical path method (John, 1988). For example, for the Hotkeys Grouped method, it was expected that the (**p**)oint operation to the first shape control point and the button clic(**k**) to issue the command would occur in parallel. Since the point operation has a longer completion time, that time was used in the prediction, while the click time was neglected (Table 6.3.3).

The KLM includes a very limited grid drawing model for shape drawing tasks. However, in this study, a simple dragging task was used as the model for this experiment's drawing task. This is because shape drawing for this task requires only the specification of two points while dragging the pointer, and is not grid-based. Previous research has found that dragging tasks tend to be about 25% slower than simple pointing tasks (MacKenzie et al., 1991). Therefore, drawing was modeled as a 1.37 second operation (1.1 sec*125%), on average.

The final addition to the model was to model the ballistic directional motion used to select commands from the marking menu as two button clicks. This time was estimated after a few observations of the motion. The ballistic, un-aimed and short mouse motion is very quick, requiring little more time than a button click.

Since the KLM was intended to predict practiced performance, it was assumed that practiced users of marking menus would issue commands before the pie menus appeared.

For this reason, the system response time for the pie menus to appear (333 ms) was left out of the calculation.

The KLM predicts a very fast input time for the new command selection technique of Bimanual Marking Menus. The KLM analysis is a useful tool for designers selecting command selection methods. Other useful tools for designers are actual studies (such as this one) which experimentally compare specific input methods. It is interesting to note that the Kabbash study's results contradict the results of the KLM prediction (i.e. the Toolglass method time prediction is higher than the predicted times for the Toolbar method). This contradiction points to the need for deeper verification of the Kabbash study, and of the KLM predictions in this paper. To this end, experimental trial times were next measured and compared to the KLM predicted values.

6.3.3 Experimental Design

The independent variables for this experiment include:

Mode: Static Toolbar (TB), Grouped Hot Keys (HKG), Mapped Hot Keys (HKM), Toolglass (TG), Marking Menu (MM), Bimanual Marking Menu (BMM)

Shape: Line, Rectangle, Oval

Size: 220 pixels on diagonal, vs. 440 pixels on diagonal

Position: 128 pixels vs. 256 pixels from screen center

There were 16 repetitions for each condition, broken into eight sequential blocks (each containing 24 trials) used to track learning effects as users became more familiar with the input methods. The measured variables were shape completion time and number of mouse clicks per shape. Using a within-subjects design, the null hypotheses that were tested included:

H_{01}: There was no difference in **average completion time** between input methods.

H_{02}: There was no difference in **learning rate** between input methods. Learning rate was calculated by measuring the improvement in average completion time over the course of the experiment.

H_{03}: There was no difference in **error rate** between input methods. If a shape was not drawn in the minimum number of mouse clicks, an error was recorded, and the error trial's time was excluded from the completion time analysis.

Testing followed a prescribed order. For each input method, all eight blocks of trials were given in series, in which the shape, size, repetition, and position were randomized within each block. Input methods were presented in randomized order, with the constraint that marking menus and bimanual marking menus were separated by three or more input methods (to reduce cross-learning, as both methods use the same menu). In addition, mapped and grouped hotkeys were separated by two or more input methods to reduce boredom. Note that it was assumed that only shape distance from the homing point, and not shape direction from the homing point had an effect on completion time. This assumption was based on the original formulation of Fitts' Law (Fitts, 1954), which has been shown to robustly predict that pointing time is solely a function of target distance and size, and ignores direction.

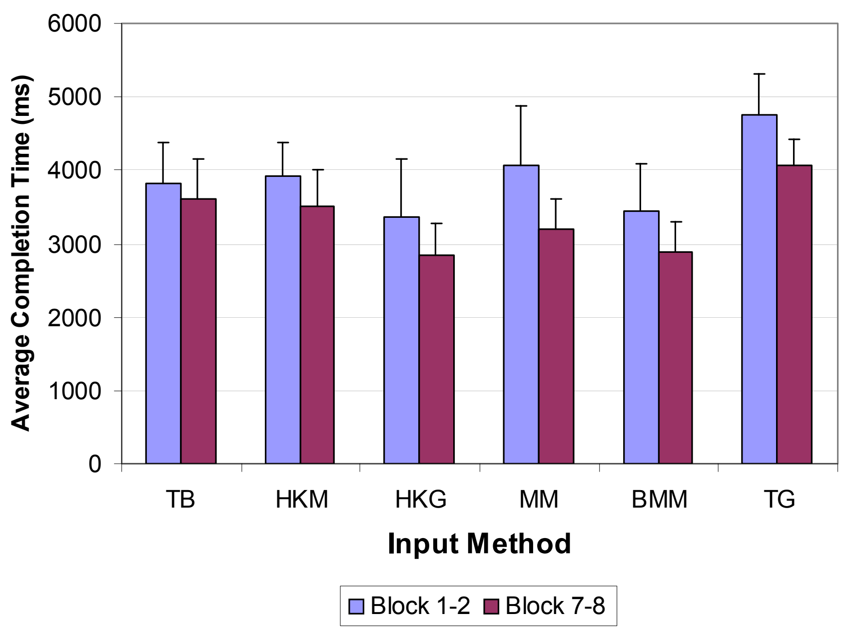
6.3.4 Participants and Environment

All testing was performed with two standard ball mice (one for each hand), and a standard 101-key keyboard. These choices were felt to best represent the standard workstation setup. Right mouse speed was set to 5 out of 11, with "low" acceleration in Win2K. Left mouse speed was controlled by the testing software, and set to a controller-to-display gain (C:D gain) of about 1:6 - roughly matching the speed of the right mouse. The testing system used a 19” monitor set to 1024x768 resolution.

Twelve volunteer engineering graduate and undergraduate students participated in this study. All had extensive previous computer experience, and used the mouse primarily with their right hand. Eleven participants were male; one was female. Student ages ranged from 21 to 31. A potential thirteenth participant’s data was discarded due to an extremely high error rate (30% for Toolbar, about 3 times higher than average), and the fact that he completed only 7 of 8 blocks for one of the input modes.

6.4 Results

The average completion times for blocks 1 and 2 (novice performance) and blocks 7 and 8 (practiced performance) are shown in Figure 6.4.1. Error bars for all graphs represent standard deviations.



Error bars represent one standard deviation. N=12

Figure 6.4.1: Completion Time by Block

As the focus of this study is practiced performance, completion time results are presented for the average of blocks 7 and 8 in Table 6.4.1. Data were analyzed with one-way ANOVA and follow-up Bonferroni t-tests (α=.05) to test the three hypotheses. **H_{01}:** For completion time, the data strongly refute the null hypothesis ($F_{5,3161}=188.98$, $p<.0001$). **H_{02}:** For learning rate, the data refute the null hypothesis ($F_{5,66}=2.76$, $p<.05$). **H_{03}:** For error rate, the data do *not* refute the null hypothesis ($F_{3,380}=2.51$, $p>.05$).

Input Method	**Toolbar (TB)**	**Toolglass (TG)**	**Marking Menu (MM)**	**Bimanual Marking Menu (BMM)**	**Hotkeys Mapped (HKM)**	**Hotkeys Grouped (HKG)**
Completion Time (ms)	3616 [a]	4067	3206	2887 [b]	3529 [a]	2846 [b]
Standard Deviation	(731)	(1052)	(620)	(726)	(849)	(642)
Total Error Rate (%)	9.98%	8.29%	10.07%	10.98%	N/A	N/A
Standard Deviation	(6.93%)	(6.06%)	(7.76%)	(6.92%)	(N/A)	(N/A)
Learning Rate (%)	5.53%*	14.11%	19.29%*	15.64%	10.21%	13.51%
Standard Deviation	(5.82%)	(7.33%)	(14.24%)	(7.22%)	(8.62%)	(12.89%)

All completion time differences are significant (p<.05) except pairs [a] and [b],
** denotes significant learning difference (p<.05)*
N=12

Table 6.4.1: Experimental Results

Error rate was calculated as the percentage of trials for which target shapes were not correctly drawn on the first attempt. Error rates for the hotkey techniques do not appear because keystroke errors were not captured by the test software. Oval trials accounted for roughly 70% of all errors. This is not surprising, since ovals display fewer cues for alignment, making them more difficult to draw. No statistically significant difference was found of the measured input method error rates.

Similarly, follow-up tests revealed statistically significant learning differences only between standard marking menus and toolbars. Not surprisingly, Static Toolbars demonstrated the smallest learning improvement, due most likely to their ubiquity in today's interfaces.

Learning rate was calculated as the percent reduction in average completion time between the first two blocks and the final two blocks of the method trial. Figure 6.4.2 tracks average completion time as a function of time for each input method from block 1 to block 8. In addition to the improvement of task completion time as a function of learning, differences between input method performances can be clearly seen from this graph.

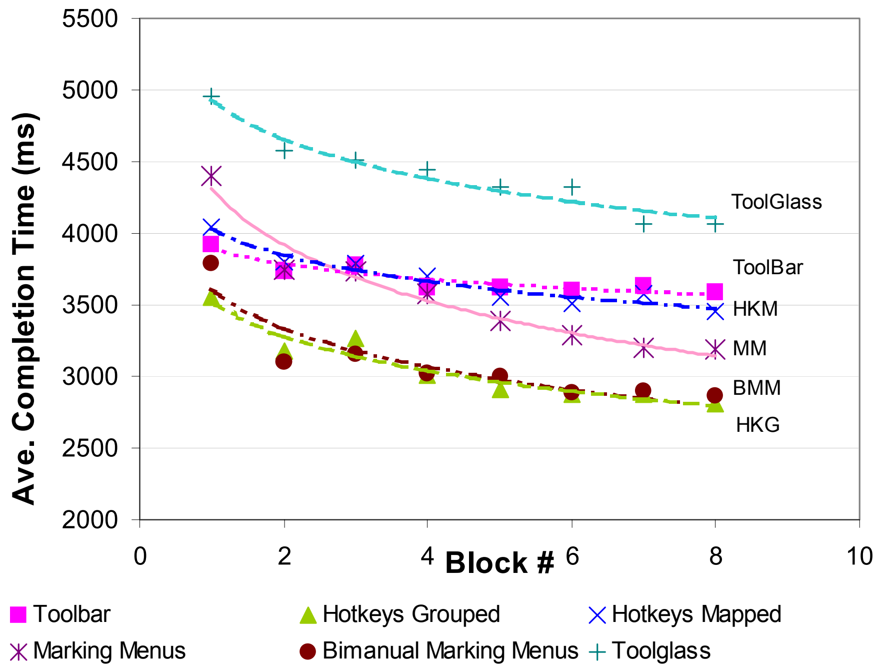


Figure 6.4.2: Average Completion Time by Block

Practiced completion times were normalized to the Toolbar completion time (the reference method); the normalized values are plotted in Figure 6.4.3. This graph is very useful because it clearly shows the relative performance of the different input methods, facilitating comparisons of their performances. All negative values represent input methods that are faster than the standard command selection method of Toolbars, while positive values represent methods that are slower than Toolbars. Therefore, lower values are more preferable as they represent faster performance.

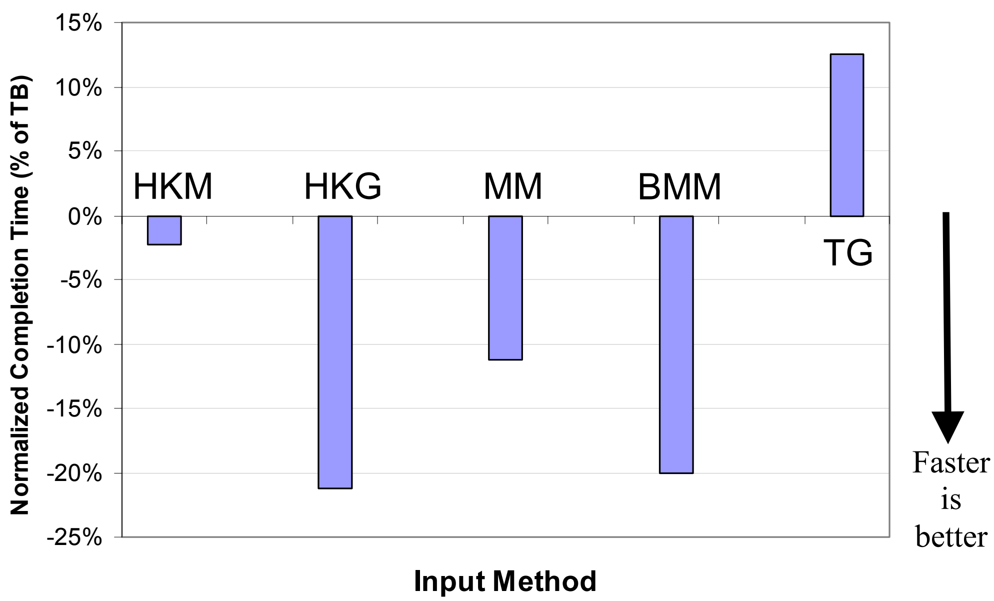


Figure 6.4.3: Completion Time Normalized to Toolbar Performance

At the conclusion of the experiment, participants were asked to rank the six input methods and respond to short-answer questions. Ranking results are shown in Table 6.4.2, and differences are statistically significant (Kendall's W = .549, X^2 (5) = 32.95, $p<.05$). Other user comments appear in the following discussion.

Input Method	Average Score	Median Score	Variance
Bimanual Marking Menu	5.25	6	1.48
Hotkeys Grouped	4.58	5	1.90
Marking Menus	3.67	4	1.70
Toolbar	3.17	3	1.97
Hotkeys Mapped	3.08	3	1.17
ToolGlass	1.25	1	.39

N=12

6=Most Favorite

1=Least Favorite

Table 6.4.2: Subjective Rankings

6.5 Discussion

Of all the tested input methods, Grouped Hotkeys and Bimanual Marking Menus were found to be the fastest. Both were statistically significantly faster than Toolbars, and neither was statistically significantly faster than the other. Toolglasses were found to be the slowest overall. It is interesting to note that the subjective rankings closely follow the quantitative speed rankings. This indicates that participants are able to effectively discern performance differences between input methods.

The performance of Static Toolbars was slightly below average, in terms of completion time, error rate and qualitative ranking. Overall, these results support the intuition that newer command selection should be strongly considered over the current standard. The implications of this study for other promising methods are explored further in the following sections.

6.5.1 Toolglass Slower than Static Toolbars?

This implementation of Toolglasses was found to be statistically significantly slower than Static Toolbars. This contradicts the findings of Kabbash et. al.(1994), whose study also compared toolbars and toolglasses. The cause of this discrepancy has not been identified conclusively, but there are several possible explanations. These are presented in decreasing order of the likely cause of this performance difference.

Input device differences

The pointing device used in this study was the standard ball mouse, the most widely used pointing device. Kabbash's study, however, used a trackball in the left hand. Also, certain implementation choices differ from Kabbash's and may have affected Toolglass performance, as well.

1. Acceleration - This study had low acceleration for the right hand, while Kabbash had no acceleration. This may have disrupted limb synchrony.
2. Control:Display Gains - The ratio of controller movement to pointer movement may have affected Toolglass performance.

Task differences

This study required users to re-center the pointer and toolglass after every completed shape, and did not display the toolglass until the homing screen disappeared. This was intended to break users' sense of continuity from shape to shape, and focus the test on command selection. Since the Toolglass required precise positioning of two onscreen objects, the need to re-acquire these objects before each task may have impaired performance.

To explore this issue further, a smaller follow-up study was performed using six of the same subjects from the previous experiment (considered to be experts with all input methods). This follow-up study used a continuous sequence of 72 randomly located and sized shapes (lines, rectangles and ovals) presented with *no homing screen*. Only Toolglass and Toolbar input methods were compared. The average completion times were 4.36 seconds for Toolbar (SD = .73), and 4.84 seconds for Toolglass (SD = 1.00), and were found to be statistically significantly different via a pairwise t-test. Thus Toolglasses were still found to be 11% slower than Toolbars, indicating that the presence of the homing screen had only a small effect, if any, on performance.

However, other drawing task differences may also have played a role. Possibilities include drawing colored lines versus shapes, or large target endpoint presentation versus no target endpoint presentation. Additionally, the transparency level of the toolglass may have had an effect.

Toolglass should disappear

Most implementations of toolglasses present the toolglass only when it is available for a valid command selection. In our implementation, the toolglass was always visible, even while shapes were being drawn. This implementation decision may have been partially responsible for user's greatest complaint about the Toolglass – that it was "distracting to use." Any toolglass motion while drawing a shape may have been visually distracting. Distraction was cited by nine of the twelve participants in the study as a reason for selecting this input method as their least favorite. Other minor differences between the studies (such as four valid menu selections vs. three valid selections) might also have had an effect.

Toolbar/Toolglass size

For this study and the Kabbash study, the *relative* size of the Toolbar and Toolglass were identical. However, the *absolute* size of the Toolglass and Toolbar appears to be bigger here than for the Kabbash study (154x115 pixels for both menu sizes in this study). This may have affected relative input method speed, as, according to Fitts' law, the effect of target width on pointing speed is non-linear.

The other possibility . . .

In addition to these possibilities, some evidence exists to suggest that Toolglasses are simply a less efficient method of command selection. Beyond the results of the present experiment, the Keystroke-Level Model predicts the largest input time for the Toolglass input method. Additionally, subjective feedback and observations suggest that users struggled with problems inherent in the Toolglass method. In the words of one participant, "toolglass required moving two cursors to the same spot, which I found split my focus." This is the very problem that the Kabbash study cited as the main problem for the other bimanual input methods tested in that study.

This problem relates to the simple fact that users must accurately position both hand inputs over the desired location when using the Toolglass method. This means that both hands must perform an aimed motion from one area of the screen to the next in concert (although the Toolglass requires a less accurate placement than the pointer). Worse, proprioception is disabled for this action because user input is provided through two *relative* input devices that are not co-located. This problem is avoided in the hotkey and marking menu methods, where the command selection does not require any aimed motion.

In summary, much of the expected benefit of the toolglass method (over static toolbars) was expected to come from the reduction of the required pointer travel distance between the workspace and the toolbar (reducing the Index of Difficulty of the pointing operations). However, this benefit seems to be offset by the requirement of performing an aimed motion operation with the non-dominant hand.

6.5.2 Evaluation of Hotkeys

Despite the fact that both Mapped and Grouped Hotkey methods use keyboard data entry, their performance was found to be statistically significantly different. Grouped Hotkeys were found to be the fastest overall, and the second most preferred. Mapped Hotkeys, on the other hand, were found to be the third slowest (but still faster than Static Toolbars), and the second least preferred. Grouped Hotkey findings reinforce the findings of a recent study (McLoone et al., 2003), which found that both dedicated and chorded hotkeys performed roughly 15% faster than static toolbars for cutting and pasting operations.

Of course, the present study represents a very simple case - where users had to select between only three keys. Due to finger reach and user memory limitations, it is unlikely that grouped hotkeys could successfully be scaled to more than approximately eight to ten commands. In contrast, Mapped Hotkeys could likely be successfully scaled to encompass very large command sets at roughly the same performance level.

As might be expected, Grouped Hotkeys (where command keys must be memorized) showed a higher learning rate than Mapped Hotkeys (where command keys have a direct cognitive mapping to the command name). In fact, the Mapped Hotkeys learning rate was second only to the static toolbar method, with which users were already expert before beginning the testing.

The main cause for the relatively slow performance of Mapped Hotkeys seemed to be the time required to look from the display to the keyboard in order to locate and select the desired command, and then look back to the display. This re-homing time was not present for the Grouped Hotkeys method, where memorized key locations were manipulated by feel.

In the Mapped Hotkey trials, several users were observed attempting to contort their hands in an uncomfortable manner to simultaneously attempt to reach the “r”, “l”, and “o” keys – thus turning Mapped Hotkeys into Grouped Hotkeys. In order to maintain the integrity of the comparison when this problem arose, the test administrator quickly reminded subjects to hold their left hand in the home position (index finger over “f”). This observation demonstrates user preference for grouped hotkeys. This also serves as a reminder that poorly designed interfaces can lead to physical discomfort for users, potentially leading to Repetitive Strain Injuries.

6.5.3 Evaluation of Bimanual Marking Menus

The new input method of Bimanual Marking Menus showed several advantages relative to the other tested input methods. It was subjectively ranked as the favorite input method overall by the test subjects, and was quantitatively found to be the second fastest overall input method (with no statistical difference between it and the fastest overall input method, Grouped Hotkeys). Also, the learning rate of bimanual marking menus was the second highest overall. This was due likely to the facts that as users memorize the command positions, users no longer need to wait for visual feedback, and that users were unaccustomed to this new input method at the beginning of testing.

Bimanual Marking Menus (BMMs) offer several benefits derived from bimanual interfaces, including:

- *reduced workload* on the dominant arm by splitting the input between two arms
- *extra degrees of freedom* available for other uses, such as magic lenses, bimanual document navigation, stretchable shapes, etc.

In addition, Bimanual Marking Menus combine these benefits with the benefits available from standard Marking Menus:

- *more available workspace* due to the elimination of static toolbars
- *novice/expert transition path* helps users memorize menu locations and increase input speed by eliminating the need for visual feedback (Kurtenbach et al., 1993)
- *no visual split* as the command menu is coupled to the pointer position
- *nested menus* allow scaling to larger command sets
- *no dedicated keys* required in hardware

BMMs operate under the Parameter/Command theory. Their implementation diverges from the Kinematic Chain theory, which states that the left hand should precede the right in the series of actions. Instead, Bimanual Marking Menus begin with a right hand motion first. Consistent with KC theory, however, Bimanual Marking Menus use the left hand only for coarse positioning (a ballistic motion is used for command selection). The left hand also sets the frame-of-reference, albeit in a difference context. In this case, the frame of reference is the commanded mode of operation.

Bimanual Marking Menus also require no state switching of the dominant hand, as do many of the other tested input methods. Since the right hand always specifies positions, and the left always specifies commands, there is no thought required to keep track of the current state of the dominant cursor.

In the test software, a new command selection had to be made for every operation. This would need to be changed for practical implementation so that command selection would persist, rather than requiring a new selection for every operation. Additionally, a method for recovering from incorrect command selection would need to be provided, since, in the current implementation, command selection is only available after the first shape control point is specified.

6.5.4 Evaluation of the Keystroke-Level Model (KLM) Predictions

Table 6.5.1 shows the KLM predicted task completion times as contrasted with the actual measured times. As this table shows, the KLM predicted completion times ranged from 24% to 32% higher than the measured times. This is higher than the error rate found in the original KLM, which was found to predict method completion times to an accuracy of roughly 12% when taking measurement standard error into account (Card et al., 1980).

To check how the *relative* input method time predictions matched the relative performance of the measured input times, all of the predicted times were normalized to the reference input method (Toolbar). This was done due to the observation that all error rates were inflated, but fell within a small band (8% difference between them). This hinted at a systematic error in the analysis.

The results of this *predicted* task time Toolbar normalization, along with the *measured* Toolbar normalized times (shown alone in figure 6.4.3) are shown in Figure 6.5.1. This figure shows that the KLM predicted task completion times closely match the measured times when the times are normalized to the Toolbar input method to show relative performance. Under these conditions, the error rate of the prediction times fall within the 12% error rate found in the original model (Table 6.5.1). This finding supports the notion of an included systematic error.

Operator	Time	**Toolbar (TB)**	**Hotkeys Mapped (HKM)**	**Hotkeys Grouped (HKG)**	**Standard Marking Menu (MM)**	**Bimanual Marking Menu (BMM)**	**Toolglass (TG)**
key click - K (.20s)	**0.2**	2	2	1	4	1	1
point - P (1.1s)	**1.1**	2	1	1	1	1	1
home - H (.40s)	**0.4**		1				
mental - M (1.35s)	**1.35**	1	1	1	1	1	2
draw - D (1.37s)	**1.37**	1	1	1	1	1	1
system - R (.33s)	**0.33**				(novice)	(novice)	
Predicted Time		**5.32**	**4.62**	**4.02**	**4.62**	**4.02**	**5.37**
Measured Time		3.62	3.53	2.85	3.21	2.89	4.07
Error %		32%	24%	29%	31%	28%	24%
Predicted Time Normalized to TB		1.000	.868	.756	.868	.756	1.009
Measured Time Normalized to TB		1.000	.976	.787	.887	.798	1.125
Normalized Error %		0.0%	-12.4%	-4.2%	-2.1%	-5.7%	-11.4%

Table 6.5.1: KLM Task Completion Predicted Times vs. Measured Times

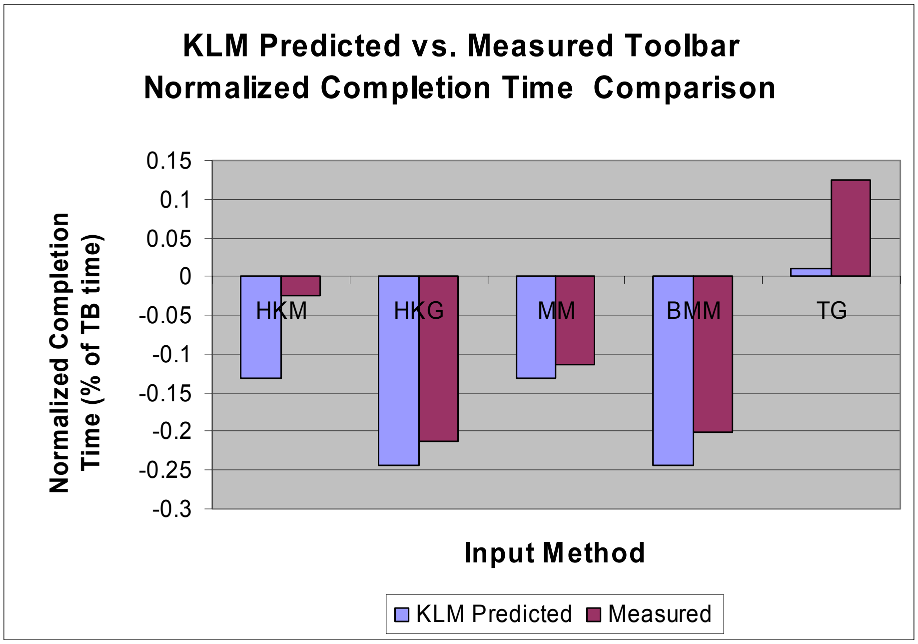


Figure 6.5.1: Completion Time Normalized to Toolbar Performance

In considering the possible inclusion of a systematic error in the KLM predictions, the original required operations were examined. Since this task was very simple, with users selecting from among only three different commands, it is reasonable to expect that practiced users were able to simply select the desired command from memory and without much thought. Using this justification, it is reasonable to remove one (**M**)ental operation from the predicted time of each input method. The results of this modification are shown in Table 6.5.2.

Operator	Time	**Toolbar (TB)**	**Hotkeys Mapped (HKM)**	**Hotkeys Grouped (HKG)**	**Standard Marking Menu (MM)**	**Bimanual Marking Menu (BMM)**	**Toolglass (TG)**
key click - K (.20s)	**0.2**	2	2	2	4	1	1
point - P (1.1s)	**1.1**	2	1	1	1	1	1
home - H (.40s)	**0.4**		1				
mental - M (1.35s)	**1.35**	0	0	0	0	0	1
draw - D (1.37s)	**1.37**	1	1	1	1	1	1
system - R (.33s)	**0.33**				(novice)	(novice)	
Predicted Time		**3.97**	**3.27**	**2.67**	**3.27**	**2.67**	**4.02**
Measured Time		3.62	3.53	2.85	3.21	2.89	4.07
Error %		8.9%	-7.9%	-6.6%	2.0%	-8.1%	-1.2%

Table 6.5.2: Modified KLM Task Completion Predicted vs. Measured Times

For this case, the KLM prediction times are much more accurate if the simplicity of the task is taken into effect, and one mental operator is removed from the prediction times. However, this would not have been known a priori, as it deviates from the rules for applying the (**M**)ental operator (as shown in Table 6.3.1). This result may hint to a necessary extension of the heuristics for applying the mental operator.

At a higher level, the results of this analysis indicate that the KLM method is still very useful for input method designers, or for designers selecting from among a variety of input methods. However, what is important for designers to consider is the *relative* performance of the input methods, rather than the absolute performance. This analysis has provided evidence to verify that the KLM is able to help designers to select the fastest input method without the need to run a comparison study.

6.5.5 Observations

One interesting phenomenon that was observed during testing was that most users would select the first shape control point on the upper left side of the shape, even if this point was the furthest of the four from the initial position of the pointer. This was done so that the mouse drag required to draw the shape could be made by moving the pointer down and to the right. When asked about this tendency, users made comments such as “I like to draw top-to-bottom and left-to-right, like with a pencil,” “For consistency – I’m just used to it, ” and “I just look at the top-left corner first.”

This is likely due to one of three effects. Either it is physiologically easier for right-handers to move a mouse down (and to the right) than up (and to the left) – a fact of which people unconsciously take advantage, or people have become accustomed to moving the input device down and to the right as this is the direction that the pointer must move from the most commonly placed toolbars to the workspace. Another possibility is that people simply tend to follow the English language standard of writing top-to-bottom and left-to-right. Further testing (either with different input devices, inexperienced computer users, or non-English speakers) could provide more insight into this.

6.6 Chapter Conclusions

This study has quantified the performance of several new and traditional input methods for a simple drawing task. In addition, qualitative feedback comparing these methods was collected from study participants. The most significant findings were as follows:

1) Grouped hotkeys were found to be the fastest overall input method.

2) The new command selection technique of Bimanual Marking Menus was found to be the second fastest and most preferred input method, and seem to provide other potential benefits that warrant further study.
3) The performance of the Toolglass input method seems to be sensitive to low-level design decisions. The particular implementation of Toolglass in this study demonstrated an inferior performance relative to previous implementations (Kabbash et al., 1994). Toolglass's reduced performance in this study must be investigated more completely. This paper has offered several ideas as to the cause of this result, and future studies will be aimed at testing these ideas.
4) Overall, the two fastest and most preferred command selection techniques were bimanual techniques. This finding highlights the power and potential inherent in bimanual input, as enabled by the Command Chair.

Bimanual Marking Menus have shown potential, performing very well in this series of tests. Future work will apply this technique in other contexts. Additionally, the Bimanual Marking Menu method will be integrated with higher-level bimanual concepts and "chunking" to further expand its capabilities. These software techniques, when combined with the physical input enabled by the Command Chair, provide an integrated bimanual computer input system enabling forms of input that were previously unavailable, and providing superior performance relative to traditional computer input workstations.

Source code for and a compiled version of the test software used in this study are available at: http://kingkong.me.berkeley.edu/html/~dano/index.htm

Chapter 7: Future Work

Future work on the Command Chair will be focused on improving its performance with respect to efficiency and comfort. With respect to efficiency, the Command Chair ball bearing transfers will be replaced with smoother bearings. As mentioned in Chapter 4, the current bearings exhibit increased friction at the spot when the bearings begin to re-circulate – resulting in a non-uniform pointer motion. Addressing this problem will likely be the most effective approach towards improving the pointing performance of the Command Chair for both speed and accuracy.

To attempt to improve the typing speed of the Command Chair the current membrane keyboard should be replaced with a keyboard that provides better tactile feedback. Beyond these changes, more significant changes such as articulating the Command Chair armature to provide a better transition between course and fine pointing may be explored. Similarly, a method for "parking" the Command Chair armature during typing may help to improve the typing speed of the Command Chair.

With respect to comfort, the most necessary change to the Command Chair is to re-align the keyboard with the forearm rest to eliminate the radial deviation of nearly 10° as measured in Chapter 4. This should be an easy modification to make, and will return the wrist to a consistently neutral position. Beyond this, palm rest adjustments should facilitate easier key reach. Finally, the Command Chair design should be adjusted to better accommodate the smallest users.

Once these changes have been made, additional testing of the Command Chair should be performed to verify the improvements. First, the newly developed workstation testing procedure, as documented in Chapter 4, should be run to measure the input performance of the improved Command Chair. This test should include wrist posture measurements to verify the wrist posture improvement has returned the wrist to a neutral position. Additionally, learning should be accounted for in both pointing and typing performance measures. Similarly, viewing distance to the monitor should be controlled and held constant between tests. The performance measures of the improved Command Chair should then be plugged back into the cost comparison model discussed in Chapter 5 in order to evaluate the overall workstation performance improvement of the Command Chair relative to a traditional workstation.

Once this testing is complete, a number of Command Chairs should be manufactured for longer term testing. In this series of tests, the Command Chair would be provided to users at their own work sites. They would use the Command Chair as their primary computer input mode for a number of months. Injury symptoms would be monitored over this period of time in order to verify the injury rate predicted in Chapter 5. Similarly, users would log their experiences of using the Command Chair to help determine longer-term learning rate, period of acclimatization, and general user feedback. In parallel with this, throughput could be measured at a very high level by monitoring employee output as a function of time both with and without the Command Chair.

On the software side, the next step will be to implement Bimanual Marking Menus into a usable system for command selection. Since to date Bimanual Marking Menus have only been implemented in a test environment, an open-ended implementation is important for real-world verification. The software will serve as a demonstration platform for exhibiting some of the benefits and power of bimanual computer input. It is envisioned that the demonstration software will operate as an intermediary to Windows™, interpreting the input from the second pointing device (e.g. the Command Chair) and providing it in a meaningful way to applications.

In additional to Bimanual Marking Menus, this software should include useful bimanual input techniques that have been previously explored. Likely candidates include a "zoom lens" and bimanual document navigation. A zoom lens is simply a virtual magnifying glass whose position is controlled by the non-dominant hand (Bier et al., 1994). Bimanual document navigation enables the non-dominant hand to reposition the document (e.g. panning) while the dominant hand maintains its typical pointing and selection role (Buxton, 1994). These techniques are relatively easy to implement and demonstrate some effective ways in which bimanual computer input can be used.

Also, a follow-up study should be undertaken to verify finding of inferior Toolglass performance relative to standard Toolbars. Several potential factors have been identified that may affect performance. These include: input device differences, task differences, toolglass persistence, and toolglass size. The effects of these factors should be determined, along with the overall relative performances of these methods.

Further in the future, independent bimanual interfacing may also be explored for manipulating several virtual objects simultaneously. This technique could prove particularly effective if the interface could take advantage of the user's sense of proprioception, the unconscious sense of limb position. Such a system would likely be extremely useful for virtual assembly applications.

Chapter 8: Conclusions

This collection of work has been geared towards exploring how bimanual computer input and forearm support can be leveraged for improved usability, efficiency, and comfort in human-computer interaction. This chapter will summarize the findings of this work.

8.1 The Benefits of Bimanual Computer Input

A new bimanual computer input technique called Bimanual Marking Menus has been developed. This technique enables users to make rapid and intuitive command selections with the non-dominant hand while, in parallel, specifying virtual parameters as usual with the dominant hand. In a study comparing the performance of a variety of one and two-handed command selection techniques, Bimanual Marking Menus were found to be the most preferred by users. Additionally, Bimanual Marking Menus were found to be roughly twenty percent faster than Static Toolbars, today's current standard, matching the fasted tested input method.

In addition to these efficiency and subjective preference benefits, this new technique provides many other benefits, as well. For a given task, it reduces the input loads on a single limb by splitting input motions between two limbs – reducing the risk of repetitive injury and improving comfort. As it makes use of a pointing device in the non-dominant hand, this command selection technique enables the use of a variety of other bimanual techniques, as well. Learning rates for Bimanual Marking Menus were not found to be significantly higher than the other input methods, indicating that they are intuitive to use.

8.2 The Benefits of Forearm Support

Experiments performed for this work have shown that forearm support provides benefits for a variety of tasks, including computer input. These benefits include significant reductions in static muscle loads in the upper extremity as well as a significant subjective reduction in shoulder effort. Furthermore, accompanying subjective improvements in forearm comfort and ease of completing tasks were found. With respect to computer input in particular, the presence of forearm support was found to provide a significant improvement in wrist posture.

These findings are important, as both static muscle load and wrist postures have previously been found to be risk factors for Musculoskeletal Disorders. Therefore, forearm support shows great promise in improving comfort and reducing injury risk in computer input. The integrated workstation approach of the Command Chair leverages this benefit for computer input.

8.3 An Integrated Computer Input System — the Command Chair

The Command Chair is new computer input workstation that integrates an office chair and forearm support with keyboard input and pointer inputs for each arm. This system takes advantage of the benefits of forearm support while simultaneously enabling the benefits of bimanual computer input. The Command Chair utilizes the integration of the keyboard and pointer input to provide a reduction in keyboard-to-pointer homing time of roughly eighty percent. Relating to usability, the learning rate of the Command Chair was found to be comparable to a traditional workstation. However, when decoupled from bimanual input, the Command Chair was measured to demonstrate slower pointing and typing speed relative to a traditional workstation.

In order to determine how this reduced efficiency compares with the comfort benefits of the Command Chair, a new technique to evaluate the overall performance of a computer input station was developed. This comparison works by normalizing workstation performance metrics to a cost basis, and then evaluating the overall cost to operate a workstation as a function of time.

Using this technique to compare the Command Chair to a traditional workstation revealed that the Command Chair is less costly to operate over time, if the device is to be used for more than thirty four days. Furthermore, the analysis revealed that the outcome is most sensitive to the efficiency of the Command Chair – meaning that future improvements in pointing and typing performance will greatly reduce the operating costs of the Command Chair.

Portions of this dissertation were written using the Command Chair

8.4 Summary of Conclusions

1) This work has shown that Bimanual Marking Menus, a new command selection technique that utilizes bimanual computer input, demonstrates increased efficiency and improved usability relative to today's standard input techniques.
2) This work has shown that forearm support provides reduced static muscle load and improved working wrist postures relative to working without forearm support. These factors correlate to a reduced risk for repetitive strain injury, and improved comfort.

3) A new integrated computer input station, the Command Chair, has been developed to take advantage of the benefits of forearm support while simultaneously providing bimanual computer input.
4) A new workstation evaluation technique demonstrates the overall benefit of the Command Chair.
5) This body of work demonstrates some ways that forearm support and bimanual computer input can be leveraged to provide usability, efficiency, and comfort in human-computer interaction.

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Appendix A: LBL Study (Chapter 2) Support Documents

This appendix includes the documentation and Committee for the Protection of Human Subjects (CPHS) approval letter for the LBL Dynamic Ergo Arm study described in Chapter 2. These documents provide the specific procedural details for this set of experiments as provided to CPHS.

A.1 Test Protocol

1. TITLE: "Ergo Arm Support R&D – Phase II: Preliminary User Field Testing and Engineering Prototype Refinement"

2. RELATED PROJECTS: none

3. NATURE AND PURPOSE:

Computer users are routinely exposed to such work situations whenever they interface with their keyboards and pointing devices. The posture of simply holding hands over the keyboard without any support other than the shoulder accelerates the onset of muscle (static) fatigue and has the potential to evolve into discomfort, pain and a strain in areas of the upper extremity musculature. The key to biomechanical relief is effective upper extremity orientation and posture. This can be achieved through a dynamic support mechanism that has the ability to: 1) facilitate an individual's biomechanical movements, 2) reduce the amount of static muscle loading, reduce the amount of physical exertion, and comfortably support a range of anthropometric dimensions of the arms. "Neutral" position is the one the body naturally assumes. It is the least stressful, strongest, and most efficient position for the body. The challenge with existing arm rest/support devices is that they are often not appropriately specified or customized to the individual worker and must be rigidly attached to a working surface. There is a need to design and fabricate a device that allows proper positioning of the entire arm aggregate resulting in benefits in the shoulder musculature.

This proposal is a continuation of the research and engineering efforts to design and develop a cost-effective and functional ergonomic support device. A working model has been created that subjectively demonstrates viability of the device to support the upper extremities and reduce the amount of dynamic muscular exertion and static muscle loading. There is optimism that this device will assist in minimizing upper extremity ergonomic injuries arising from awkward postures and repetitive movements. Reduction in muscle fatigue and discomfort associated with use of the upper extremities can be realized from utilization of this apparatus.

The objective of Phase II is to collect additional user feedback through a written survey, as well as collect preliminary electromyographic (EMG) measurement data to develop the existing engineering model into a functional prototype and pursuit of a CRADA. Some subjective verbal feedback has been received to date, but a more formal record of data is now needed. Field-testing of the apparatus on several volunteer users will occur in this phase. With the assistance the University of California Ergonomics Program (1301 South 46th Street, Building 163, Richmond CA 94804 - Dr. Robert Goldberg, M.D. and Alan Barr, Development Engineer), non-invasive surface electrodes will be placed onto the skin of individuals to measure electrical muscle activity at various static and dynamic postural positions and range of movements, as taken from individual's upper extremities. The data collected will help to better understand if and how the device reduces muscular effort to during neutral and working positions, as well as provide information for further design enhancements and engineering prototype development.

4. SUBJECTS: Ten volunteer subjects, five of each sex, will be solicited from the Berkeley Lab working population.

5. RECRUITMENT: Subjects will be solicited through a flyer distributed to the Safety Coordinators and with an electronic announcement in "Today at Berkeley Lab". Interested volunteers will be directed to contact the EH&S Division Occupational Safety Group for further information about the study and consent forms.

6. SCREENING PROCEDURES: There are two restrictions that would preclude a prospective volunteer subject from participating in the study: (1) if the subject is experiencing upper extremity musculoskeletal discomfort or has been diagnosed with musculoskeletal disorder by a healthcare professional and (2) if the subject is allergic to the adhesive material used for the surface EMG procedure. No further screening is involved. All volunteers will be accepted up until five of each sex is obtained.

7. PROCEDURES:

Volunteer subjects will be solicited from the Berkeley Lab workforce to participate in this field study. The volunteer subjects will not be required to use annual/vacation leave while they are participating in the research. Those who have expressed interest will be provided with a handout package that contains an overview of the study, synopsis experimental protocol, supervisor approval form, and consent documents. They will be asked to complete all forms before eligibility is considered. Each subject will be scheduled for a 4-hour field-testing session and completion of the survey instrument during the workday. The subjects will report to the apparatus room, wearing a tank top T-shirt, be provided with an orientation of electromyography, view the EMG instrumentation and receive instructions about the test measurement process and scenarios they would be involved with. Skin surface preparation (shaving, if necessary of a 1' x 2"skin surface area and wiping the area with alcohol) and attachment of the surface electrodes (above conduction gel) would be occurring, followed by the field test session and completion of the survey form. Five (5) surface electrodes will be placed along various muscle groups of the forearms, upper arms, upper back and shoulders. This electro diagnosis instrumentation will help quantify changes in muscular activity during use of the experimental apparatus, while performing various upper extremity postural positions and movements. EMG data collected from volunteer subjects will help with the assessment and refinement of this engineered experimental apparatus. The subjects will be videotaped to document the research process; the video recording equipment will be in plain sight.

Based on the following Experimental Protocol Summary Table, each subject will be asked to participate in two ways: (1) while connected to an EMG instrument, operate the ergo arm support device under a variety of established working scenarios and (2) completion of an evaluation survey. Employees will be provided short breaks (~5-10 minutes) between each measurement sessions to enable the research team to set up for the subsequent test scenarios.

Measurement Conditions	EMG Activity of Muscle Groups (mV)	**Subjective Feedback From Survey Form**
Sitting – Without Device**:** Neutral Position (arms at rest and ~90 degree angle)		
Sitting – With Device: Neutral Position (arms at rest and ~ 90 degree angle)		
Sitting – Without Device and Keyboard Use		
Sitting – With Device and Keyboard Use		
Sitting – Without Device and Mouse Use		
Sitting – With Device and Mouse Use		
Sitting – Without Device Reaching		
Sitting – With Device Reaching		
Sitting – Without Device Arm Swinging		
Sitting – With Device Arm Swinging		
Standing – Without Device: Neutral Position (arms at rest and ~90 degree angle)		
Standing – With Device: Neutral Position (arms at rest and ~90 degree angle)		
Standing – Without Device: Using Soldering Gun		
Standing – With Device: Reaching		
Standing – With Device Arm Swinging		
Standing – Without Device Arm Swinging		
Standing – With Device Simulated Drilling		
Standing – Without Device		

Simulated Drilling		
Standing – With Device Static Extended Arm Posture		
Standing – Without Device Static Extended Arm Posture		

8. BENEFITS: There are no foreseeable benefits to the subjects. The hope is that information obtained from the subjects can be applied towards improving and refining this engineered ergonomic support device. The resultant device could then become available to the general workforce by providing an additional level of comfort, support and safety for computer users and other workers that rely on use of the upper extremities in the workplace.

9. RISKS: The risks are primarily social in nature. The subjects might be embarrassed if their video and digital photos were publicly disclosed. Also, because of the routine nature and duration of the test protocol, fatigue and boredom may occur with the subject(s). It is believed that its risks are outweighed by the potential benefit to safety in the workplace the eventual engineered ergonomic device will provide.

10. CONFIDENTIALITY: Confidentiality will be protected by procedures of secure management of videotapes, digital photographs and notes. The tapes and records of each subject will be identified only by code number. The faces of each participating subject will be digitally altered in the photos and videotapes to assure confidentiality. The potentially identifiable records will be kept in a locked file in the principal investigators office. The list associating the subjects with code numbers will be locked in a separate location. When compiling data, subjects will be referred to by code number. Published reports of the study will involve only aggregate summaries, statistical evaluations and digital photos with the faces masked. If data or videotapes are made available to other researcher or commercial developers, subjects will remain anonymous and be referenced only by their assigned code number.

11. INFORMED CONSENT: The consent procedure will take place before the experiment during the screening process. Once a qualified subject agrees to participate, s/he will be asked to sign the Consent Form (see attachment). A copy of the Informed Consent form will be given to each of the subjects for their personal record.

After a subject has participated in the experiment, a full debriefing, and an explanation as to how the data will be utilized and published. Each subject will be asked to sign the standard CPHS Video/Photo Release Form (see attachment). A copy of this form will be given to each of the subjects for their personal record.

12. FINANCIAL ASPECTS: None.

13. WRITTEN MATERIALS: (see attachments)

A.2 Apparatus Evaluation Forms

Task Feedback

Subject Number: ______________________________ **Date:** __________________

Task:____

Please provide us with some feedback about your experience with and without the ergonomic arm support device while performing this task.

Select a location along the line (by drawing a vertical line at the selected location) that best describes the…

1. …ease of completing the task:

With the Ergonomic Device

5 **4** **3** **2** **1**
Difficult Easy

Without the Ergonomic Device

5 **4** **3** **2** **1**
Difficult Easy

2. … amount of shoulder effort required to complete the task:

With the Ergonomic Device

5 **4** **3** **2** **1**
Difficult Easy

Without the Ergonomic Device

5 **4** **3** **2** **1**
Difficult Easy

3. …level of forearm comfort while performing the task:

With the Ergonomic Device

5 **4** **3** **2** **1**
Uncomfortable Comfortable

Without the Ergonomic Device

5 **4** **3** **2** **1**
Uncomfortable Comfortable

Post Field Test Questionnaire
Subject #: _____

Thank you for volunteering to be a participant in the testing and evaluation of our ergonomic arm support device. We will also need to collect some anthropometric data from you:

Sitting Elbow Height: __________

Standing Sternal Notch Height: _________

Height: __________

Weight (lbs.): ___ (< – 115) ___ (115 – 135) ___ (135 – 155) ___ (155 – 175) ___ (>175)

A. With your arms in the device, did you feel: (please circle one answer)
   1. Fully supported
   2. Somewhat supported
   3. No difference
   4. Somewhat loss of control
   5. Complete loss of control

B. With your arms supported by the device, how did your arms feel? (please circle one answer)
   1. Much lighter
   2. Somewhat lighter
   3. About the same
   4. Somewhat heavier
   5. Much heavier

C. When you performed the variety of tasks with the device, how much effort did you need to exert? (please circle one answer)
   1. A lot less effort to perform the tasks
   2. Somewhat less effort to perform the tasks
   3. Same amount of effort to perform the tasks as without the device
   4. Somewhat more effort to perform the tasks
   5. A lot more effort to perform the tasks

D. If you had an opportunity to name this device, what would you suggest?

E. Are there any additional comments or suggestions you would like to share with us to improve this device?

A.3 Volunteer Subject Orientation Packet

Dear Prospective Field Test Subject:

Thank you for your inquiry and interest to become a volunteer user for the field-testing of our novel “engineered” Ergonomic Arm Support System. The criteria for participation are as follows:

- Supervisor’s permission to spend 4 hours away from your work location during one workday to participate in the field-testing (see attached form #1).
- Ability to schedule 4 consecutive hours away from your job during one workday in order to participate in the field-testing.
- No currently diagnosed upper extremity musculoskeletal injury or discomfort (self-disclosure).
- No known allergies to the adhesive material used for the surface EMG procedure.
- Completion of consent forms (see attached forms).

The field-testing will involve placement of electrodes on your skin surface to measure electromyographic measurements (electrical muscle activity) during various static and dynamic positions. Joint angles will also be physically measured. Video and digital photographs of your upper extremities positions and movements will also be recorded. These recordings will be kept anonymous by digitally altering your face. Your test data will also be kept confidential and only be referenced by a code number.

If you have any questions about the research, you may call either Dr. Chung or Dr. Siminovitch. If you have any questions about your rights or treatment as a participant in this research project, please contact the Berkeley Lab, Human Subjects Committee at (510) 486-6267, email: PDLichty@lbl.gov

Please review the materials and if you concur with the conditions for participation. If you remain interested, complete the consent forms, obtain the necessary signatures, and return the packet to Jeffrey Chung.

Thank you again for your interest.

Jeffrey Chung, PhD (EH&S)

Michael Siminovitch, Ph.D (EETD)

Steve Dellinges (Engineering Designworks)

Robin Lafever (Engineering Designworks)

ERNEST ORLANDO LAWRENCE
BERKELEY NATIONAL LABORATORY

A.4: Standard Consent Form

PURPOSE AND BACKGROUND

You are volunteering to participate in a research study conducted by Jeffrey Chung, Ph.D, Michael Siminovitch, Ph.D, Steve Dellinges and Robin Lafever of Lawrence Berkeley National Laboratory. You will not be using your vacation time or be placed on unpaid leave status.

This LBNL internally funded study is a continuation of the research and development efforts to create a cost-effective and functional ergonomic arm support device. A working model has been built. The purpose of this phase is to formally collect user feedback through a written survey, as well as collect preliminary electromyographic (EMG) measurement data to develop the existing engineering model into a functional engineering prototype.

1. **PROCEDURES. If you agree to be in this study, the following will happen**:

    - You will report to the apparatus evaluation room and be provided with an orientation of electromyography, view the EMG instrumentation and receive instructions about the test measurement and test protocol you will participate in. <u>Please wear a tank top</u>.

    - Your skin will be prepared and surface electrodes will be attached for EMG monitoring. There will be a total of six (6) surface electrodes attached to various muscle groups of your forearms, upper arms, shoulders and upper back during your session to help us test the efficacy of the device. This electro diagnosis instrumentation will help quantify changes in muscular activity during use of the experimental apparatus, while performing various upper extremity postural positions and movements.

    - You will be asked to participate in two ways: (1) while connected to an EMG instrument, operate the ergo arm support device under a variety of established working scenarios and (2) completion of an evaluation survey.

      EMG data collected from you will help with the assessment and refinement of this engineered experimental apparatus.

- During the testing session, your upper torso/extremities will be photographed with a digital camera while assuming various static positions. Movements of your upper torso/extremities will also be recorded on videotape when you are utilizing the experimental apparatus.

You will have the opportunity to review any digital photos and videotaping that is recorded during your test session. We will require your consent for their use at the conclusion of the experiment. Your face will be digitally altered to assure confidentiality.

2. RISKS/DISCOMFORTS

The risks are minimal. You may find some of your recorded data and video/digital photo documentation collectively published or displayed. Your features will be digitally altered so you will not be recognizable.

EMG measurements may create a slight "tingly sensation" across the muscle groups where the surface electrodes are placed on the top of your skin. We will take care to minimize these risks. It is believed that its risks are outweighed by the potential benefit to safety in the workplace by obtaining this data and using it to refine the apparatus into an "engineered" prototype.

3. BENEFITS

There are no foreseeable benefits to the subjects. The hope is that information obtained from the subjects can be applied towards improving and refining this engineered ergonomic support device. The resultant device could then become available to the general workforce by providing an additional level of comfort, support and safety for computer users and other workers that rely on use of the upper extremities in the workplace.

4. STORAGE OF SAMPLES/DATA

Your upper extremity's joint angles will be physically measured and documented onto a log. Your postural positions and movements will be recorded as EMG measurements. All of the information that we obtain from your field-testing session will be kept confidential by assigning you a test subject code number. The potentially identifiable records will be kept in a locked file in the principal investigator's office. The list associating the subjects with their respective code numbers will be locked in a separate location. If the data are published or made available to other researchers or commercial developers, you will remain anonymous and you will be referenced only by your assigned code number or your data displayed in aggregate with other test subjects' data. We will not use your name or identifying information in any reports of our research.

The digital photographs and videotape recordings of your test session will be kept anonymous by digitally altering your face to assure confidentiality. We will store the digital photos and video recordings in a locked cabinet. We will use a code number to identify your digital photos and videotaped recordings. We will keep your name and your code number in a separate locked location. We will not use your name, face or identifying information in any published research reports. If the photos or video recordings are made available to other researchers or commercial developers, you will remain anonymous by having your face digitally altered and referenced only by your assigned code number

5. FINANCIAL CONSIDERATIONS

There will be no compensation to you for participating in this study.

6. QUESTIONS

Any further questions you have about taking part in this study will be answered by: Dr. Jeffrey Chung or Dr. Michael Siminovitch.

Any questions you have about your rights as a research subject will be answered by: Berkeley Lab Human Subjects Committee at (510) 486-5507)

If you have any questions abut your rights or treatment as a participant in this research project, please contact the University of California at Berkeley's Committee for Protection of Human Subjects at (510) 642-7461, or e-mail: subjects@uclink4.berkeley.edu

7. ALTERNATIVES [None]

8. PARTICIPATION IN RESEARCH IS VOLUNTARY.

You have the right to not take part in this study or to stop taking part at any time. You will be given a copy of this consent form to keep. If you wish to participate, you should sign below.

AUTHORIZATION. I have read this consent form. All of the questions I asked have been answered to my satisfaction. I have neither been diagnosed with any musculoskeletal disorder by a licensed healthcare professional nor am I currently experiencing any musculoskeletal discomfort. I wish to volunteer to participate in this research.

___ ______

Date Subject's Signature

______

Subject's Name (print legibly)

A.5: Medical Research Subjects' Bill of Rights

California law and University of California policies require that any person asked to take part as a subject in research involving a medical experiment, or any person asked to consent to such participation on behalf of another, is entitled to receive the following list of rights written in a language in which the person is fluent.

This list includes the right to:

1) Be informed of the nature and purpose of the experiment.

2) Be given an explanation of the procedures to be followed in the medical experiment, and any drug or device to be utilized.

3) Be given a description of any attendant discomforts and risks reasonably to be expected from the experiment.

4) Be given an explanation of any benefits to the subject reasonably to be expected from the experiment, if applicable.

5) Be given a disclosure of any appropriate alternative procedures, drugs or devices that might be advantageous to the subject, and their relative risks and benefits.

6) Be informed of the avenues of medical treatment, if any, available to the subject after the experiment if complications should arise.

7) Be given the opportunity to ask any questions concerning the experiment or the procedures involved.

8) Be instructed that consent to participate in the medical experiment may be withdrawn at any time and the subject may discontinue participation in the medical experiment without prejudice.

9) Be given a copy of the signed and dated written consent form.

10) Be given the opportunity to decide to consent or not to consent to a medical experiment without the intervention of any elements of force, fraud, deceit, duress, coercion, or undue influence on the subject's decision.

A.6: CPHS Experiment Approval Letter

BERKELEY:COMMITTEE FOR PROTECTION
OF HUMAN SUBJECTS
101 WHEELER HALL, MC #1340
642-7461 * FAX: 643-6272
subjects@uclink4.berkeley.edu

July 15, 2003

JEFFREY CHUNG, Ph.D.
MICHAEL SIMINOVITCH, Ph.D.
STEVEN DELLINGES
ROBIN LAFEVER
Lawrence Berkeley National Laboratory

Re: "Ergo Arm Support R&D – Phase II: Preliminary User Field Testing and Engineering Prototype Refinement" – Departmental Research with Departmental Funding

Thank you for sending your revised protocol and consent forms relating to the project referred to above. They satisfy the Committee's conditions and we are pleased to grant full approval.

The number of this project remains 2003-8-10. Please continue to refer to this number in all future correspondence about the project.

The expiration date of this approval is June 11, 2004. Approximately six weeks before the expiration date, we will send you a continuation/renewal request form. Please fill out the form and return it to the Committee, according to the instructions. If you do not receive these forms in a timely manner, please contact the CPHS Office at (510) 642-7461, or visit our website at http://cphs.berkeley.edu.

Attached is a copy of the consent materials reviewed by the Committee; the expiration date of the Committee's review of this form is noted on it. Please copy and use this stamped consent form for the coming year.

Please note that even though the Committee has approved your project, you must bring promptly to our attention any changes in the design or conduct of your research that affect human subjects. If any of your subjects experience any untoward events in the course of this research, you must inform the Committee within ten (10) working days.

If you have any questions regarding this matter, please contact the CPHS staff at 642-7467, FAX 643-6272, e-mail: adelphia@uclink4.berkeley.edu.

Sincerely,

Jane Gilbert Mauldon

Jane Gilbert Mauldon
Chair, Committee for Protection of Human Subjects
Associate Professor, Goldman School of Public Policy

JGM:amb

UNIVERSITY OF CALIFORNIA (Letterhead for Interdepartmental Use)

A.7: Compiled Post-test Questionnaire Data

Ease of Completing Task

Task	1 to 2		3 to 4		5 to 6		7 to 8		9 to 10		11 to 12		13 to 14		15 to 16		17 to 18		19 to 20	
Subject	With	Without	With	Without	With	Without	With	Without	With	Without	With	Without	With	Without	With	Without	With	Without	With	Without
1	2	3	2	3	3	2	3	2	2	2	1.5	3	1.5	2.7	3.5	3	3	2.5		
2	1	2	2	2	2	3.5	2	3	1	1.5	1	2	2	2	3	3	2	4		
3	1	3	2	3.5	3	2	1	2	2	1	1	2	1.5	1	2	2	2	1		
4	1	2	2.5	3	2.25	3.25	2.5	2.25	2	2.5	1.75	2.5	1.75	2.25	1.75	3.75	3.25	4.25	1.75	3.5
5	1.25	2.75	1	2.5	1	2.25	1	1.75	1.25	1.4	1	2.8	1	3.5	1	4.25	3.5	3.5	1.2	3.5
6	2.4	3.5	3.25	2.25	3.75	3.5	3.4	2.75	3.75	2.5	1.75	2.25	1.5	2.75	3.75	2.25	3.25	2.25	2.5	2.5
7	1	2.75	2.4	1.75	1.5	3.5	3.2	1.6	2.75	1.75	1	2.5	1	1.75	1	2.5	2.25	1.75	1	2.8
8	1	1	1	2	3	2	2	2	2	3	1	2	2	2	1	2	1	2	1	3
9	1	4	1	4	2	3	3	2	1	3	1	3	1	3	1	4	2	4	1	4
10	1	1	1	3	2.5	1	2	3	2.5	3	1.5	2	1.5	2	3	1.5	2.5	3.5	1.5	2
11	1.25	2	2	1.5	3	1.25	2	1.5	2	2.5	1.5	2	1	2	2.5	1.5	2	1.5	1	1.5

Amount of Shoulder Effort

Task	1 to 2		3 to 4		5 to 6		7 to 8		9 to 10		11 to 12		13 to 14		15 to 16		17 to 18		19 to 20	
Subject	With	Without	With	Without	With	Without	With	Without	With	Without	With	Without	With	Without	With	Without	With	Without	With	Without
1	1.25	2	1.5	3	2	3	2	3	1.9	4	1.5	3.5	1.5	3	2	3	2	3.5		
2	1	2	2	3	2	4	2	3	1	1	1	2	1	2	2.5	3.5	2	4		
3	1	3	1	4	2	3.5	1	3	1	1	1	3	1	2.5	1	3	2	4		
4	1.5	2.5	2	3.5	2.25	3.25	2.25	2.5	1.75	2.5	1.5	2.5	1.75	2.8	2	3.25	3	4.25	1.75	3.5
5	1	2.75	1	3.25	1	3.3	1	2.4	1	2.3	1	2.25	1	3.25	1	4.4	3.5	3.25	1	3.5
6	2.5	3.5	2.25	3.75	2.75	3.75	2.25	3.75	3.5	3.75	1.75	2.25	1.75	3.25	3.75	3.5	2.5	3.5	2.25	3.25
7	1.5	3.75	1.4	2.75	1.5	3.5	2.25	2.25	1.75	3.2	1	1.8	1	1.6	1	1.5	1.4	2.5	1	1.6
8	1	2	1	2	3	2	2	2	1.5	2	1	2	2	2	1	2	1	2	2	3
9	1	3	1	2	1	3	3	3	1	3	1	3	1	4	2	4	2	4	1	3
10	1	1	1	1	2	1.5	1	1	1	1	1	1	1	1	1	1	2	3	1	1
11	1	1.75	1.5	1.5	1	1.5	1.5	1.5	2	1.5	1.25	1.25	1	2	2	3	2	3	1.25	3.5

Forearm Comfort

Task	1 to 2		3 to 4		5 to 6		7 to 8		9 to 10		11 to 12		13 to 14		15 to 16		17 to 18		19 to 20	
Subject	With	Without	With	Without	With	Without	With	Without	With	Without	With	Without	With	Without	With	Without	With	Without	With	Without
1	1.5	3	2	2	2	3.5	3	2	2	2	1.5	2	1.5	1.5	2.5	2.5	2.8	3.25		
2	3	3	3	3	2	3.5	3	3	1	3	1	2	2	2	3	3	2.5	5		
3	1	3.5	1	3	4	2	1	2	1	1	1	3	1	2	1	2	1	3.5		
4	2	2	2	2.5	1.75	3.25	2	2.5	1.75	2.5	1.5	2.5	1.75	2	2	3.5	3.5	4	2.25	3.5
5	1	3.25	1	1.75	1	2.25	1.25	1.5	1	1.75	1	1.75	1	2.25	1	2.25	3.75	3.25	1	2.4
6	2.75	3.25	1.75	3.5	3.25	3.75	2.25	3.25	2.5	2.5	2.25	3.25	1.3	2.75	2.25	3.75	2.75	3.8	2.5	3.25
7	1.2	2.75	1.5	1.5	1.5	2	1.25	1.5	1.4	2.5	1	2	1	1.75	1	2	1.25	2.5	1	2.75
8	1	2	1	2	3	2	3	2	2	3	1	2	2	3	1	2	1	2	2	3
9	1	2	1	4	1	4	3	4	1	3	1	4	1	3	1	4	2	4	1	4
10	1	2	1	2.5	3	1.5	1.5	3	2.5	3	1.5	2	1.5	2	3.5	1.5	3	3.5	1.5	2
11	1.25	2	1.25	1.75	3	2.25	1	1.5	3	3	1.75	3	1.5	1.5	2	3	3	4	2	3

A.8: EMG Readings (normalized to Maximum Voluntary Contraction)

APDF#	APDF10	APDF10	APDF10	APDF10	APDF10	APDF10	APDF10	APDF10	APDF10	APDF10
Device	without	with	without	with	without	with	without	with	without	with
Group	MidTrap	MidTrap	LatTri	LatTri	UppTrap	UppTrap	ForExt	ForExt	SupSpin	SupSpin
user1	1.77%	0.43%	0.20%	0.28%	5.65%	1.93%	2.38%	0.07%	2.51%	0.63%
user2	1.20%	1.44%	0.56%	0.39%	4.00%	1.71%	1.82%	1.18%	2.03%	2.19%
user3	1.99%	0.75%	1.62%	0.45%	3.72%	0.33%	7.94%	6.56%	4.06%	0.30%
user4	3.86%	3.76%	0.80%	2.13%	1.00%	0.89%	3.02%	3.46%	1.16%	0.86%
user5	6.07%	1.01%	1.04%	1.48%	5.65%	2.30%	3.83%	1.42%	7.70%	2.79%
user6	0.33%	0.26%	0.66%	0.51%	0.69%	0.97%	10.85%	9.73%	0.72%	0.52%
user7	0.63%	0.47%	0.92%	0.59%	3.03%	1.18%	10.93%	9.25%	1.54%	0.53%
user8	0.88%	0.00%	1.18%	0.24%	1.95%	0.32%	6.19%	3.34%	3.06%	0.15%
user9	5.66%	1.19%	0.80%	0.57%	1.93%	2.72%	10.14%	4.06%	2.24%	3.28%
user10	2.85%	2.12%	1.64%	0.75%	1.37%	1.26%	5.25%	4.62%	2.88%	2.28%
user11	0.74%	0.66%	0.71%	0.32%	0.41%	0.39%	2.01%	1.37%	1.20%	0.49%
Average	2.36%	1.10%	0.92%	0.70%	2.67%	1.27%	5.85%	4.10%	2.65%	1.27%
Ave. Difference	1.26%		0.22%		1.40%		1.75%		1.37%	
StDev.	2.02%	1.06%	0.43%	0.58%	1.88%	0.81%	3.59%	3.24%	1.94%	1.13%
T-test Paired	0.043586		0.321088		0.018133		0.0071		0.030617	

APDF#	APDF50	APDF50	APDF50	APDF50	APDF50	APDF50	APDF50	APDF50	APDF50	APDF50
Device	without	with	without	with	without	with	without	with	without	with
Group	MidTrap	MidTrap	LatTri	LatTri	UppTrap	UppTrap	ForExt	ForExt	SupSpin	SupSpin
user1	2.58%	0.65%	0.30%	0.43%	7.54%	2.63%	3.16%	0.15%	3.46%	0.91%
user2	1.51%	1.96%	0.67%	0.44%	5.21%	2.17%	2.67%	1.87%	2.61%	2.99%
user3	3.10%	1.05%	2.22%	0.91%	5.61%	0.49%	10.69%	9.27%	6.21%	0.46%
user4	4.79%	4.61%	1.06%	2.72%	1.27%	1.13%	3.97%	4.75%	1.50%	1.10%
user5	8.53%	1.67%	1.37%	2.27%	7.97%	3.57%	5.13%	2.19%	10.37%	4.20%
user6	0.49%	0.40%	0.84%	0.65%	0.94%	1.34%	14.14%	13.32%	0.94%	0.73%
user7	0.88%	0.65%	1.17%	0.76%	4.84%	1.66%	15.50%	13.15%	2.29%	0.70%
user8	1.29%	0.00%	1.50%	0.27%	2.76%	0.40%	9.12%	5.14%	4.30%	0.17%
user9	7.85%	1.48%	0.98%	0.64%	2.71%	3.55%	14.15%	5.42%	3.16%	4.05%
user10	3.86%	2.86%	2.13%	0.94%	1.89%	1.75%	8.07%	6.51%	3.91%	3.12%
user11	0.93%	0.84%	0.90%	0.36%	0.50%	0.48%	3.17%	2.08%	1.54%	0.61%
Average	3.25%	1.47%	1.20%	0.94%	3.75%	1.74%	8.16%	5.81%	3.66%	1.73%
Ave. Difference	1.78%		0.25%		2.00%		2.36%		1.93%	
StDev.	2.79%	1.31%	0.58%	0.80%	2.63%	1.14%	4.90%	4.46%	2.68%	1.53%
T-test Paired	0.04086		0.379421		0.014816		0.010396		0.024694	

APDF#	APDF95	APDF95	APDF95	APDF95	APDF95	APDF95	APDF95	APDF95	APDF95	APDF95
Device	without	with	without	with	without	with	without	with	without	with
Group	MidTrap	MidTrap	LatTri	LatTri	UppTrap	UppTrap	ForExt	ForExt	SupSpin	SupSpin
user1	3.96%	1.09%	0.46%	0.70%	11.22%	3.96%	4.69%	0.27%	5.07%	1.50%
user2	2.26%	3.09%	0.91%	0.51%	7.49%	3.11%	4.23%	3.72%	3.60%	4.54%
user3	5.08%	1.96%	3.26%	1.12%	9.22%	0.69%	15.98%	14.64%	10.16%	0.75%
user4	6.67%	6.41%	1.67%	3.92%	1.93%	1.85%	5.83%	7.36%	2.25%	1.83%
user5	13.29%	3.15%	2.02%	4.24%	12.44%	5.90%	7.58%	3.89%	15.68%	7.03%
user6	1.44%	1.32%	1.23%	0.90%	1.48%	2.05%	20.11%	21.56%	1.47%	1.21%
user7	1.38%	1.15%	1.68%	1.13%	7.65%	3.82%	25.40%	21.45%	3.62%	2.29%
user8	2.06%	0.00%	2.12%	0.30%	4.32%	0.63%	14.55%	9.23%	6.56%	0.22%
user9	12.31%	2.09%	1.38%	0.78%	4.23%	5.19%	21.94%	8.11%	4.85%	5.69%
user10	5.73%	4.65%	3.12%	1.30%	2.98%	2.84%	13.03%	10.12%	6.06%	4.75%
user11	1.41%	1.33%	1.35%	0.42%	0.77%	0.77%	5.64%	3.59%	2.15%	0.85%
Average	5.06%	2.38%	1.75%	1.39%	5.79%	2.80%	12.64%	9.45%	5.59%	2.79%
Ave. Difference	2.67%		0.35%		2.99%		3.19%		2.80%	
StDev.	4.26%	1.84%	0.86%	1.37%	4.04%	1.80%	7.58%	7.12%	4.15%	2.31%
T-test Paired	0.047174		0.443568		0.016284		0.030349		0.030982	

Data Summary for Task 1-2, Seated Static 90°

APDF#	APDF10	APDF10	APDF10	APDF10	APDF10	APDF10	APDF10	APDF10	APDF10	APDF10
Device	without	with	without	with	without	with	without	with	without	with
Group	MidTrap	MidTrap	LatTri	LatTri	UppTrap	UppTrap	ForExt	ForExt	SupSpin	SupSpin
user1	1.01%	1.12%	0.15%	0.07%	6.07%	6.28%	2.27%	2.34%	1.21%	1.06%
user2	1.04%	1.01%	0.60%	0.39%	1.52%	1.16%	4.77%	4.71%	1.95%	0.89%
user3	1.85%	0.86%	1.57%	0.86%	2.74%	0.45%	7.63%	5.90%	2.92%	0.48%
user4	4.96%	4.36%	0.80%	0.67%	2.59%	2.12%	4.11%	3.16%	4.32%	2.95%
user5	6.06%	1.04%	1.04%	0.78%	5.14%	0.99%	2.40%	2.46%	7.34%	1.66%
user6	0.36%	0.21%	0.96%	0.58%	0.65%	0.45%	9.27%	8.37%	0.95%	0.50%
user7	0.49%	0.56%	0.95%	0.65%	1.10%	1.26%	11.17%	7.98%	0.81%	0.68%
user8	1.13%	0.42%	1.13%	0.29%	1.72%	0.40%	5.86%	3.42%	2.48%	0.12%
user9	3.80%	4.92%	0.87%	0.55%	9.56%	6.28%	6.78%	9.67%	9.81%	7.63%
user10	3.17%	1.09%	1.83%	0.64%	1.20%	0.55%	6.34%	2.42%	3.01%	0.50%
user11	1.01%	0.70%	0.58%	0.35%	0.61%	0.40%	2.25%	1.96%	1.53%	0.74%
Average	2.26%	1.48%	0.95%	0.53%	2.99%	1.85%	5.71%	4.76%	3.30%	1.56%
Ave. Difference	0.78%		0.42%		1.14%		0.95%		1.74%	
StDev.	1.94%	1.60%	0.46%	0.23%	2.81%	2.25%	2.93%	2.79%	2.86%	2.16%
T-test Paired	0.140397		0.002289		0.027378		0.121613		0.004719	

APDF#	APDF50	APDF50	APDF50	APDF50	APDF50	APDF50	APDF50	APDF50	APDF50	APDF50
Device	without	with	without	with	without	with	without	with	without	with
Group	MidTrap	MidTrap	LatTri	LatTri	UppTrap	UppTrap	ForExt	ForExt	SupSpin	SupSpin
user1	1.52%	1.78%	0.24%	0.12%	8.26%	8.63%	3.23%	3.38%	1.73%	1.87%
user2	1.33%	1.51%	0.76%	0.45%	1.97%	1.42%	7.10%	6.68%	2.72%	1.61%
user3	3.09%	3.10%	2.14%	1.06%	5.10%	0.57%	12.10%	8.75%	5.29%	0.90%
user4	6.83%	5.87%	1.00%	0.87%	4.74%	4.00%	5.58%	4.28%	6.18%	5.14%
user5	10.23%	5.55%	1.47%	1.08%	7.83%	4.14%	3.55%	3.49%	11.38%	7.38%
user6	0.67%	0.35%	1.35%	0.86%	1.18%	0.60%	13.60%	12.81%	1.50%	0.89%
user7	0.65%	1.61%	1.25%	0.89%	1.47%	1.98%	16.53%	14.58%	1.46%	2.31%
user8	1.85%	0.65%	1.53%	0.42%	2.84%	0.59%	16.30%	5.41%	4.10%	0.33%
user9	5.93%	7.36%	1.20%	0.65%	14.17%	10.23%	9.00%	13.20%	15.01%	12.55%
user10	4.74%	1.72%	2.52%	0.84%	1.75%	1.05%	9.27%	6.02%	4.41%	0.95%
user11	1.49%	0.89%	0.81%	0.42%	1.55%	0.48%	3.93%	3.68%	3.58%	1.27%
Average	3.48%	2.76%	1.30%	0.70%	4.62%	3.06%	9.11%	7.48%	5.21%	3.20%
Ave. Difference	0.72%		0.60%		1.56%		1.63%		2.01%	
StDev.	3.09%	2.40%	0.63%	0.31%	4.06%	3.43%	4.95%	4.21%	4.31%	3.76%
T-test Paired	0.205237		0.002165		0.014925		0.172318		0.003739	

APDF#	APDF95	APDF95	APDF95	APDF95	APDF95	APDF95	APDF95	APDF95	APDF95	APDF95
Device	without	with	without	with	without	with	without	with	without	with
Group	MidTrap	MidTrap	LatTri	LatTri	UppTrap	UppTrap	ForExt	ForExt	SupSpin	SupSpin
user1	2.45%	3.24%	0.39%	0.27%	12.47%	13.53%	5.59%	5.72%	2.72%	3.59%
user2	2.19%	3.56%	1.06%	0.57%	2.93%	2.00%	11.13%	10.35%	4.14%	3.68%
user3	5.26%	6.96%	3.15%	2.58%	9.17%	0.93%	19.49%	14.19%	9.35%	1.70%
user4	10.71%	9.08%	1.43%	1.49%	8.17%	7.42%	8.58%	6.79%	9.52%	8.93%
user5	17.64%	12.87%	2.24%	1.67%	13.22%	9.68%	5.65%	5.39%	18.53%	16.63%
user6	1.84%	1.28%	2.03%	1.49%	2.20%	1.02%	21.56%	21.77%	2.51%	1.62%
user7	1.06%	4.17%	1.85%	1.36%	2.44%	5.04%	27.36%	24.52%	2.48%	5.25%
user8	3.23%	1.68%	2.31%	0.88%	5.08%	1.74%	29.35%	8.90%	7.81%	2.05%
user9	9.90%	11.59%	1.83%	0.99%	22.97%	17.78%	13.35%	19.49%	24.28%	21.23%
user10	7.45%	3.42%	3.86%	1.51%	2.82%	2.32%	14.47%	11.01%	6.95%	2.69%
user11	2.58%	1.53%	1.22%	0.66%	4.73%	0.71%	9.01%	7.48%	6.55%	2.21%
Average	5.85%	5.40%	1.94%	1.22%	7.84%	5.65%	15.05%	12.33%	8.62%	6.33%
Ave. Difference	0.45%		0.72%		2.18%		2.72%		2.30%	
StDev.	5.13%	4.12%	0.97%	0.64%	6.39%	5.80%	8.32%	6.75%	6.95%	6.66%
T-test Paired	0.562085		0.004764		0.038977		0.198179		0.03195	

Data Summary for Task 3-4, Seated Arm Sweeping

APDF# Device Group	APDF10 without MidTrap	APDF10 with MidTrap	APDF10 without LatTri	APDF10 with LatTri	APDF10 without UppTrap	APDF10 with UppTrap	APDF10 without ForExt	APDF10 with ForExt	APDF10 without SupSpin	APDF10 with SupSpin
user1	1.61%	0.25%	0.32%	0.17%	5.63%	0.25%	5.37%	6.63%	1.97%	1.05%
user2	1.04%	1.15%	0.69%	0.44%	1.01%	0.73%	3.50%	3.20%	1.05%	1.67%
user3	1.24%	0.00%	2.19%	0.91%	0.60%	0.45%	7.75%	7.24%	0.42%	0.62%
user4	3.34%	3.12%	1.14%	0.64%	0.06%	0.81%	3.46%	4.50%	1.05%	0.95%
user5	1.28%	0.73%	1.28%	0.93%	1.66%	0.00%	4.75%	3.71%	3.41%	0.87%
user6	0.27%	0.10%	0.68%	0.68%	0.72%	0.38%	11.63%	11.71%	0.55%	0.78%
user7	0.62%	0.00%	1.05%	0.62%	1.17%	0.07%	13.79%	15.65%	2.58%	0.86%
user8	0.46%	0.61%	1.26%	0.37%	0.45%	0.01%	6.40%	4.42%	0.00%	0.00%
user9	1.41%	1.37%	0.84%	0.82%	0.86%	0.00%	7.55%	6.46%	1.04%	1.21%
user10	1.96%	1.32%	1.95%	1.02%	0.76%	0.39%	8.30%	5.49%	2.02%	0.90%
user11	0.83%	0.71%	0.75%	0.36%	0.44%	0.00%	1.69%	1.56%	1.16%	0.00%
Average	1.28%	0.85%	1.10%	0.63%	1.22%	0.28%	6.74%	6.42%	1.39%	0.81%
Ave. Difference	0.43%		0.47%		0.93%		0.33%		0.58%	
StDev.	0.85%	0.91%	0.56%	0.27%	1.52%	0.30%	3.61%	4.05%	1.01%	0.48%
T-test Paired	0.01967		0.003059		0.080765		0.452999		0.080526	

APDF# Device Group	APDF50 without MidTrap	APDF50 with MidTrap	APDF50 without LatTri	APDF50 with LatTri	APDF50 without UppTrap	APDF50 with UppTrap	APDF50 without ForExt	APDF50 with ForExt	APDF50 without SupSpin	APDF50 with SupSpin
user1	2.54%	2.02%	0.77%	0.57%	9.12%	8.47%	7.96%	9.43%	2.91%	2.44%
user2	1.66%	1.69%	1.14%	0.60%	2.16%	1.26%	5.63%	6.29%	4.35%	3.52%
user3	1.90%	0.26%	3.10%	1.20%	0.84%	0.55%	11.95%	11.06%	1.36%	1.01%
user4	4.19%	4.13%	1.79%	1.93%	0.51%	1.13%	4.91%	5.93%	3.72%	1.91%
user5	2.74%	3.29%	2.27%	1.65%	3.93%	3.88%	6.76%	5.24%	5.27%	3.99%
user6	1.17%	0.81%	2.89%	1.35%	1.36%	0.86%	17.06%	18.54%	2.26%	1.81%
user7	0.80%	1.87%	1.44%	0.97%	1.51%	3.53%	18.71%	22.40%	3.74%	5.31%
user8	0.81%	2.76%	1.83%	1.03%	0.94%	1.41%	10.00%	8.07%	0.76%	2.88%
user9	2.73%	5.37%	1.47%	1.61%	2.40%	6.14%	11.39%	9.93%	5.06%	7.39%
user10	2.86%	3.41%	2.84%	1.65%	1.10%	1.17%	11.38%	8.13%	2.87%	3.18%
user11	1.19%	1.02%	1.14%	0.48%	0.66%	0.00%	3.69%	2.44%	2.27%	0.74%
Average	2.05%	2.42%	1.88%	1.19%	2.23%	2.58%	9.95%	9.77%	3.14%	3.11%
Ave. Difference	-0.37%		0.69%		-0.35%		0.18%		0.03%	
StDev.	1.06%	1.54%	0.79%	0.50%	2.49%	2.66%	4.82%	5.87%	1.44%	1.95%
T-test Paired	0.330436		0.005103		0.420446		0.768894		0.938733	

APDF# Device Group	APDF95 without MidTrap	APDF95 with MidTrap	APDF95 without LatTri	APDF95 with LatTri	APDF95 without UppTrap	APDF95 with UppTrap	APDF95 without ForExt	APDF95 with ForExt	APDF95 without SupSpin	APDF95 with SupSpin
user1	4.65%	7.35%	2.14%	1.98%	15.86%	20.12%	13.15%	14.70%	5.01%	7.92%
user2	2.66%	4.42%	1.93%	1.31%	3.82%	3.19%	9.40%	11.17%	8.27%	6.19%
user3	3.09%	3.85%	5.01%	4.47%	1.61%	0.81%	20.21%	18.18%	2.54%	1.67%
user4	6.02%	8.00%	3.15%	5.52%	1.53%	1.94%	7.99%	8.84%	7.07%	4.69%
user5	6.51%	9.96%	4.49%	3.18%	7.32%	14.26%	10.55%	8.08%	9.57%	14.65%
user6	2.40%	7.64%	8.30%	4.84%	3.52%	6.52%	28.09%	31.67%	4.34%	5.70%
user7	1.17%	10.77%	2.18%	2.97%	2.40%	18.84%	28.15%	36.96%	5.51%	21.73%
user8	1.30%	7.35%	3.14%	2.53%	2.27%	3.86%	16.63%	15.52%	3.18%	7.10%
user9	4.41%	15.25%	2.77%	5.43%	6.20%	17.57%	18.59%	16.25%	8.92%	21.53%
user10	4.68%	7.27%	4.75%	3.15%	1.98%	3.34%	17.17%	13.06%	4.70%	8.39%
user11	1.83%	1.88%	1.90%	0.69%	1.09%	2.48%	9.75%	4.19%	3.62%	2.90%
Average	3.52%	7.61%	3.61%	3.28%	4.33%	8.45%	16.33%	16.24%	5.70%	9.32%
Ave. Difference	-4.09%		0.33%		-4.12%		0.09%		-3.61%	
StDev.	1.85%	3.62%	1.93%	1.63%	4.31%	7.59%	7.10%	9.88%	2.41%	6.95%
T-test Paired	0.003103		0.542671		0.030781		0.939464		0.072113	

Data Summary for Task 5-6, Seated Arm Reaching

APDF# Device Group	APDF10 without MidTrap	APDF10 with MidTrap	APDF10 without LatTri	APDF10 with LatTri	APDF10 without UppTrap	APDF10 with UppTrap	APDF10 without ForExt	APDF10 with ForExt	APDF10 without SupSpin	APDF10 with SupSpin
user1	1.21%	0.83%	0.34%	0.28%	4.62%	3.04%	6.49%	5.45%	1.07%	0.63%
user2	1.04%	1.01%	0.55%	0.41%	1.94%	1.22%	5.95%	5.31%	1.71%	1.23%
user3	0.77%	0.80%	1.78%	1.57%	0.85%	2.08%	10.44%	8.60%	1.10%	2.06%
user4	2.06%	3.89%	0.79%	1.29%	1.53%	3.78%	4.10%	3.70%	1.94%	4.61%
user5	2.62%	1.66%	0.89%	0.85%	2.76%	1.96%	4.58%	4.84%	3.87%	6.81%
user6	0.66%	0.76%	1.57%	0.97%	0.70%	1.09%	6.37%	3.54%	1.21%	1.37%
user7	0.87%	1.46%	0.91%	0.80%	1.41%	4.12%	5.32%	7.10%	1.67%	3.38%
user8	0.92%	0.43%	1.32%	0.21%	1.53%	0.44%	4.89%	3.25%	2.54%	0.00%
user9	4.80%	3.17%	0.66%	0.63%	6.81%	5.08%	6.94%	9.83%	8.41%	5.64%
user10	2.98%	3.35%	1.41%	0.70%	0.84%	1.91%	9.32%	7.80%	2.12%	3.76%
user11	0.88%	0.79%	0.50%	0.38%	0.43%	0.41%	3.93%	2.88%	0.77%	0.52%
Average	1.71%	1.65%	0.97%	0.73%	2.13%	2.28%	6.21%	5.66%	2.40%	2.73%
Ave. Difference	0.06%		0.24%		-0.16%		0.55%		-0.33%	
StDev.	1.30%	1.23%	0.47%	0.42%	1.95%	1.54%	2.08%	2.35%	2.17%	2.27%
T-test Paired	0.82414		0.091957		0.739873		0.297976		0.580242	

APDF# Device Group	APDF50 without MidTrap	APDF50 with MidTrap	APDF50 without LatTri	APDF50 with LatTri	APDF50 without UppTrap	APDF50 with UppTrap	APDF50 without ForExt	APDF50 with ForExt	APDF50 without SupSpin	APDF50 with SupSpin
user1	2.18%	2.01%	0.46%	0.39%	7.74%	5.87%	14.21%	12.19%	2.17%	2.05%
user2	1.35%	1.73%	0.78%	0.52%	2.57%	1.54%	12.63%	10.21%	2.81%	2.32%
user3	3.27%	3.47%	3.42%	3.25%	2.05%	4.02%	20.37%	17.68%	2.76%	4.23%
user4	3.55%	7.27%	1.03%	2.12%	2.88%	6.55%	8.79%	8.39%	3.51%	8.23%
user5	5.30%	5.63%	1.39%	2.66%	4.99%	4.71%	9.65%	11.37%	6.97%	18.56%
user6	1.27%	2.69%	2.73%	1.72%	1.04%	3.28%	14.88%	11.23%	2.23%	2.77%
user7	1.33%	4.05%	1.36%	1.39%	2.44%	10.57%	11.27%	20.24%	2.86%	8.14%
user8	1.69%	2.21%	1.96%	1.03%	2.77%	0.62%	15.05%	13.72%	4.55%	0.28%
user9	7.75%	5.09%	0.87%	0.83%	11.18%	7.79%	11.77%	15.92%	13.61%	8.73%
user10	4.69%	4.65%	2.06%	0.87%	1.19%	2.72%	17.50%	13.86%	3.26%	5.38%
user11	1.27%	1.19%	1.10%	0.84%	0.53%	0.51%	11.20%	10.75%	1.28%	1.06%
Average	3.06%	3.64%	1.56%	1.42%	3.58%	4.38%	13.39%	13.23%	4.18%	5.61%
Ave. Difference	-0.58%		0.14%		-0.80%		0.16%		-1.43%	
StDev.	2.12%	1.89%	0.90%	0.92%	3.23%	3.14%	3.45%	3.52%	3.46%	5.23%
T-test Paired	0.273438		0.565406		0.431601		0.892234		0.326247	

APDF# Device Group	APDF95 without MidTrap	APDF95 with MidTrap	APDF95 without LatTri	APDF95 with LatTri	APDF95 without UppTrap	APDF95 with UppTrap	APDF95 without ForExt	APDF95 with ForExt	APDF95 without SupSpin	APDF95 with SupSpin
user1	4.28%	4.16%	0.87%	1.09%	13.29%	10.21%	34.17%	34.35%	4.49%	4.70%
user2	2.33%	3.38%	1.48%	1.33%	3.81%	2.17%	25.43%	21.18%	4.93%	4.82%
user3	11.06%	12.12%	7.31%	7.21%	4.52%	7.58%	45.56%	39.29%	6.03%	7.85%
user4	6.61%	13.65%	1.61%	4.05%	5.47%	10.88%	21.60%	20.35%	6.42%	14.01%
user5	10.79%	14.22%	3.72%	6.21%	8.95%	9.67%	22.67%	26.56%	12.47%	38.73%
user6	2.64%	8.50%	4.93%	3.26%	1.84%	7.76%	32.76%	30.15%	3.61%	6.49%
user7	2.26%	7.44%	2.74%	3.70%	6.54%	18.71%	36.13%	72.82%	5.02%	14.01%
user8	3.62%	5.83%	3.60%	3.46%	4.84%	1.32%	40.09%	36.90%	8.12%	2.04%
user9	12.62%	8.36%	1.37%	1.69%	18.44%	13.03%	21.25%	28.02%	21.84%	14.48%
user10	7.91%	7.25%	3.51%	1.27%	1.96%	4.30%	40.96%	34.10%	5.57%	8.70%
user11	2.72%	2.39%	2.77%	2.50%	0.81%	0.84%	26.85%	26.60%	2.60%	2.83%
Average	6.08%	7.94%	3.08%	3.25%	6.41%	7.86%	31.59%	33.67%	7.37%	10.79%
Ave. Difference	-1.86%		-0.17%		-1.45%		-2.08%		-3.41%	
StDev.	3.93%	4.01%	1.87%	2.01%	5.33%	5.47%	8.55%	14.33%	5.46%	10.29%
T-test Paired	0.092725		0.712269		0.365621		0.583947		0.237465	

Data Summary for Task 7-8, Seated Typing

APDF#	APDF10	APDF10	APDF10	APDF10	APDF10	APDF10	APDF10	APDF10	APDF10	APDF10
Device	without	with	without	with	without	with	without	with	without	with
Group	MidTrap	MidTrap	LatTri	LatTri	UppTrap	UppTrap	ForExt	ForExt	SupSpin	SupSpin
user1	0.53%	0.50%	0.39%	0.31%	1.29%	2.33%	6.53%	5.25%	1.04%	0.56%
user2	0.86%	0.85%	0.41%	0.58%	2.13%	1.07%	6.02%	4.36%	1.63%	0.83%
user3	2.87%	0.82%	0.83%	2.72%	1.43%	0.53%	15.61%	18.30%	1.60%	0.57%
user4	1.08%	0.95%	1.13%	1.33%	1.16%	0.77%	4.35%	3.59%	1.20%	0.92%
user5	0.87%	0.99%	1.69%	2.01%	0.78%	0.80%	2.16%	3.19%	1.33%	1.32%
user6	0.47%	0.33%	1.85%	0.63%	0.59%	0.51%	8.29%	7.77%	1.02%	0.75%
user7	0.55%	0.48%	0.79%	0.77%	1.01%	0.71%	14.96%	13.19%	1.30%	0.83%
user8	0.49%	0.62%	0.66%	0.97%	0.45%	0.40%	15.11%	14.23%	0.54%	0.31%
user9	5.22%	2.14%	0.55%	0.56%	6.23%	3.34%	7.52%	5.88%	8.84%	3.91%
user10	1.36%	0.99%	0.86%	0.80%	0.52%	0.44%	3.90%	5.80%	1.14%	0.70%
user11	0.68%	0.69%	0.42%	0.45%	0.40%	0.42%	5.80%	2.85%	0.55%	0.44%
Average	1.36%	0.85%	0.87%	1.01%	1.45%	1.03%	8.20%	7.67%	1.84%	1.01%
Ave. Difference	0.51%		-0.14%		0.43%		0.53%		0.82%	
StDev.	1.45%	0.48%	0.50%	0.74%	1.67%	0.94%	4.82%	5.20%	2.35%	1.00%
T-test Paired	0.136556		0.529625		0.181524		0.32775		0.077992	

APDF#	APDF50	APDF50	APDF50	APDF50	APDF50	APDF50	APDF50	APDF50	APDF50	APDF50
Device	without	with	without	with	without	with	without	with	without	with
Group	MidTrap	MidTrap	LatTri	LatTri	UppTrap	UppTrap	ForExt	ForExt	SupSpin	SupSpin
user1	0.77%	0.78%	0.65%	0.40%	2.66%	3.22%	10.24%	8.62%	1.51%	0.91%
user2	1.11%	1.19%	0.48%	0.86%	2.83%	1.29%	10.58%	7.79%	2.46%	1.19%
user3	4.36%	1.11%	0.96%	4.24%	2.32%	0.70%	23.79%	26.60%	2.65%	0.89%
user4	1.46%	1.35%	1.63%	1.90%	1.74%	1.00%	6.97%	5.59%	1.80%	1.26%
user5	1.64%	3.41%	3.19%	3.44%	1.24%	1.31%	4.66%	5.24%	2.40%	2.98%
user6	0.95%	1.05%	2.98%	1.13%	0.87%	0.72%	14.80%	14.34%	1.57%	1.17%
user7	0.72%	0.65%	1.27%	1.23%	1.32%	1.36%	22.84%	23.51%	2.33%	1.44%
user8	1.25%	2.43%	1.29%	1.92%	0.69%	0.56%	22.60%	22.46%	1.26%	0.61%
user9	7.51%	3.56%	0.66%	0.65%	9.51%	5.18%	11.89%	9.18%	12.93%	6.31%
user10	2.07%	1.39%	1.23%	1.10%	0.72%	0.56%	6.39%	8.27%	1.62%	0.93%
user11	0.91%	0.88%	0.57%	0.63%	0.50%	0.51%	11.42%	7.28%	1.06%	0.54%
Average	2.07%	1.62%	1.36%	1.59%	2.22%	1.49%	13.29%	12.62%	2.87%	1.66%
Ave. Difference	0.45%		-0.24%		0.73%		0.67%		1.21%	
StDev.	2.08%	1.04%	0.93%	1.23%	2.55%	1.44%	6.89%	7.85%	3.38%	1.68%
T-test Paired	0.400928		0.529325		0.109825		0.319902		0.058126	

APDF#	APDF95	APDF95	APDF95	APDF95	APDF95	APDF95	APDF95	APDF95	APDF95	APDF95
Device	without	with	without	with	without	with	without	with	without	with
Group	MidTrap	MidTrap	LatTri	LatTri	UppTrap	UppTrap	ForExt	ForExt	SupSpin	SupSpin
user1	1.47%	2.65%	1.24%	1.49%	4.85%	5.62%	22.43%	19.30%	2.60%	3.16%
user2	2.05%	2.15%	0.86%	1.50%	4.61%	1.76%	20.00%	13.65%	4.85%	2.22%
user3	7.41%	2.59%	1.37%	6.80%	4.34%	1.42%	39.06%	42.64%	5.09%	2.03%
user4	3.73%	4.03%	2.62%	3.21%	3.10%	1.65%	12.69%	9.86%	3.26%	2.76%
user5	3.50%	7.03%	5.49%	5.70%	2.98%	2.93%	10.67%	9.96%	4.79%	5.27%
user6	2.53%	2.78%	5.49%	2.47%	1.61%	1.32%	26.76%	25.07%	2.71%	2.12%
user7	1.22%	1.13%	2.16%	2.31%	2.07%	5.48%	39.48%	47.66%	4.33%	2.86%
user8	3.11%	5.60%	2.58%	3.60%	1.46%	1.02%	35.34%	36.30%	3.08%	1.56%
user9	12.13%	6.14%	0.97%	0.88%	15.99%	8.83%	18.80%	15.03%	21.14%	10.43%
user10	4.18%	3.17%	3.92%	2.20%	1.48%	1.16%	11.38%	13.83%	2.92%	1.78%
user11	2.29%	1.53%	1.74%	1.73%	0.77%	0.72%	18.52%	13.83%	2.62%	0.88%
Average	3.97%	3.53%	2.59%	2.90%	3.93%	2.90%	23.19%	22.47%	5.22%	3.19%
Ave. Difference	0.44%		-0.31%		1.03%		0.73%		2.03%	
StDev.	3.19%	1.94%	1.68%	1.85%	4.24%	2.61%	10.66%	13.59%	5.37%	2.65%
T-test Paired	0.614725		0.625562		0.22771		0.58082		0.054899	

Data Summary for Task 9-10, Seated Mousing

APDF#	APDF10	APDF10	APDF10	APDF10	APDF10	APDF10	APDF10	APDF10	APDF10	APDF10
Device	without	with	without	with	without	with	without	with	without	with
Group	MidTrap	MidTrap	LatTri	LatTri	UppTrap	UppTrap	ForExt	ForExt	SupSpin	SupSpin
user1	1.87%	0.28%	0.40%	0.26%	5.79%	0.92%	1.23%	0.27%	2.49%	0.29%
user2	0.79%	0.74%	0.52%	0.38%	1.47%	1.20%	3.03%	1.76%	0.97%	0.80%
user3	3.54%	0.69%	1.78%	0.79%	2.93%	0.39%	8.60%	3.94%	2.88%	0.65%
user4	1.23%	0.92%	0.90%	0.58%	0.96%	0.76%	4.81%	3.63%	1.33%	1.01%
user5	3.52%	1.70%	0.87%	1.34%	4.46%	3.10%	3.98%	0.56%	5.07%	3.29%
user6	0.29%	0.66%	0.60%	0.47%	0.86%	1.05%	8.01%	1.14%	0.53%	0.92%
user7	0.57%	1.50%	0.99%	0.52%	1.10%	3.61%	12.30%	14.52%	0.99%	1.81%
user8	3.49%	0.45%	0.94%	0.27%	0.96%	0.39%	1.85%	1.75%	1.85%	0.20%
user9	1.11%	2.75%	0.58%	0.67%	0.92%	6.56%	5.63%	6.58%	0.70%	7.07%
user10	2.83%	1.32%	2.07%	1.03%	0.87%	0.51%	9.01%	6.01%	2.14%	1.06%
user11	0.92%	0.71%	0.89%	0.61%	0.59%	0.56%	1.99%	0.80%	1.24%	0.50%
Average	1.83%	1.07%	0.96%	0.63%	1.90%	1.73%	5.49%	3.72%	1.84%	1.60%
Ave. Difference	0.77%		0.33%		0.17%		1.77%		0.23%	
StDev.	1.28%	0.71%	0.52%	0.33%	1.74%	1.94%	3.57%	4.18%	1.31%	2.01%
T-test Paired	0.123081		0.033662		0.837058		0.045772		0.754436	

APDF#	APDF50	APDF50	APDF50	APDF50	APDF50	APDF50	APDF50	APDF50	APDF50	APDF50
Device	without	with	without	with	without	with	without	with	without	with
Group	MidTrap	MidTrap	LatTri	LatTri	UppTrap	UppTrap	ForExt	ForExt	SupSpin	SupSpin
user1	2.64%	0.35%	0.49%	0.28%	7.95%	1.35%	1.68%	0.30%	3.37%	0.34%
user2	0.98%	0.93%	0.62%	0.42%	1.86%	1.45%	4.65%	2.85%	1.19%	0.96%
user3	5.19%	0.90%	2.28%	0.90%	4.20%	0.47%	12.00%	5.51%	4.29%	0.84%
user4	1.98%	1.19%	1.21%	0.67%	1.42%	0.96%	6.25%	4.94%	2.20%	1.24%
user5	5.15%	2.65%	1.14%	2.02%	6.29%	5.63%	5.46%	1.56%	7.14%	5.43%
user6	0.42%	1.18%	0.76%	0.59%	1.19%	1.54%	10.93%	9.98%	0.71%	1.38%
user7	0.93%	2.77%	1.28%	0.63%	3.46%	6.49%	18.02%	20.77%	2.43%	4.20%
user8	4.76%	1.15%	1.20%	0.32%	1.31%	0.49%	4.60%	3.57%	2.49%	0.29%
user9	1.93%	3.81%	0.70%	0.78%	1.18%	8.96%	7.92%	8.66%	0.98%	9.73%
user10	3.79%	1.78%	2.68%	1.32%	1.20%	0.67%	12.44%	8.66%	2.92%	1.45%
user11	1.07%	0.84%	1.05%	0.66%	0.65%	0.62%	3.17%	1.05%	1.58%	0.58%
Average	2.62%	1.60%	1.22%	0.78%	2.79%	2.60%	7.92%	6.17%	2.66%	2.40%
Ave. Difference	1.02%		0.44%		0.19%		1.75%		0.26%	
StDev.	1.81%	1.05%	0.68%	0.50%	2.42%	2.97%	4.90%	5.84%	1.83%	2.93%
T-test Paired	0.134838		0.04769		0.863855		0.037876		0.803941	

APDF#	APDF95	APDF95	APDF95	APDF95	APDF95	APDF95	APDF95	APDF95	APDF95	APDF95
Device	without	with	without	with	without	with	without	with	without	with
Group	MidTrap	MidTrap	LatTri	LatTri	UppTrap	UppTrap	ForExt	ForExt	SupSpin	SupSpin
user1	4.12%	0.63%	0.68%	0.31%	11.97%	2.33%	2.61%	0.33%	5.08%	0.57%
user2	1.64%	1.67%	0.81%	0.49%	2.59%	1.93%	7.80%	5.20%	1.88%	1.63%
user3	8.17%	1.99%	3.34%	1.04%	6.68%	0.63%	18.53%	8.73%	7.00%	1.22%
user4	3.80%	3.16%	1.93%	0.86%	2.48%	1.36%	9.08%	7.75%	3.76%	1.88%
user5	8.21%	4.43%	1.68%	3.89%	9.80%	9.70%	8.28%	4.16%	10.96%	8.82%
user6	1.21%	2.24%	1.15%	0.82%	1.85%	2.54%	17.12%	16.49%	1.19%	2.21%
user7	1.96%	4.96%	1.88%	0.89%	6.80%	10.34%	30.52%	32.88%	4.34%	6.95%
user8	7.01%	2.46%	1.72%	0.61%	1.95%	0.71%	9.23%	10.03%	3.73%	0.66%
user9	4.06%	5.79%	0.93%	1.03%	1.87%	13.52%	13.01%	12.74%	1.96%	14.84%
user10	5.86%	2.96%	3.98%	1.90%	1.94%	1.22%	18.69%	13.70%	4.49%	2.25%
user11	1.89%	1.65%	1.44%	0.73%	0.79%	0.75%	5.60%	1.60%	2.19%	0.80%
Average	4.36%	2.90%	1.78%	1.14%	4.43%	4.09%	12.77%	10.33%	4.23%	3.80%
Ave. Difference	1.45%		0.63%		0.34%		2.44%		0.43%	
StDev.	2.61%	1.57%	1.04%	1.00%	3.77%	4.69%	7.93%	9.02%	2.80%	4.54%
T-test Paired	0.127358		0.108725		0.837186		0.034041		0.780349	

Data Summary for Task 11-12, Standing Static 90°

APDF# Device Group	APDF10 without MidTrap	APDF10 with MidTrap	APDF10 without LatTri	APDF10 with LatTri	APDF10 without UppTrap	APDF10 with UppTrap	APDF10 without ForExt	APDF10 with ForExt	APDF10 without SupSpin	APDF10 with SupSpin
user1	0.46%	0.72%	0.38%	0.28%	2.19%	3.80%	2.58%	4.31%	0.58%	0.75%
user2	1.02%	0.92%	0.58%	0.39%	1.76%	1.28%	5.04%	5.11%	1.58%	0.94%
user3	1.38%	0.51%	1.52%	0.85%	0.67%	0.39%	3.08%	1.53%	0.83%	0.52%
user4	3.04%	0.99%	0.74%	0.65%	1.54%	0.51%	3.43%	3.10%	3.68%	0.97%
user5	3.14%	2.32%	1.08%	1.04%	4.81%	2.78%	2.96%	3.39%	6.04%	4.14%
user6	0.27%	0.46%	1.28%	0.40%	1.22%	0.67%	8.56%	11.04%	1.25%	0.71%
user7	0.51%	0.43%	1.03%	0.62%	0.88%	0.86%	10.79%	12.40%	0.85%	0.63%
user8	1.75%	0.23%	1.19%	0.27%	2.81%	0.22%	8.85%	1.78%	4.35%	0.00%
user9	1.24%	1.45%	0.89%	0.53%	1.47%	1.16%	9.08%	7.01%	1.25%	0.64%
user10	2.51%	2.54%	1.99%	1.11%	1.62%	1.19%	6.98%	3.00%	2.68%	2.54%
user11	0.97%	0.87%	0.76%	0.52%	0.79%	0.61%	2.29%	2.44%	1.04%	0.52%
Average	1.48%	1.04%	1.04%	0.61%	1.80%	1.23%	5.78%	5.01%	2.19%	1.12%
Ave. Difference	0.44%		0.43%		0.57%		0.78%		1.07%	
StDev.	1.02%	0.76%	0.45%	0.29%	1.18%	1.10%	3.14%	3.67%	1.78%	1.18%
T-test Paired	0.088015		0.001813		0.113301		0.377506		0.026843	

APDF# Device Group	APDF50 without MidTrap	APDF50 with MidTrap	APDF50 without LatTri	APDF50 with LatTri	APDF50 without UppTrap	APDF50 with UppTrap	APDF50 without ForExt	APDF50 with ForExt	APDF50 without SupSpin	APDF50 with SupSpin
user1	0.72%	1.09%	0.51%	0.33%	4.48%	5.56%	5.67%	6.58%	0.91%	1.19%
user2	1.57%	1.33%	0.73%	0.46%	2.29%	1.59%	7.56%	7.59%	2.71%	1.67%
user3	2.66%	2.37%	2.19%	1.04%	1.71%	0.50%	9.89%	3.93%	2.11%	0.79%
user4	5.39%	1.38%	0.92%	0.86%	3.67%	0.70%	4.87%	4.49%	5.55%	1.52%
user5	7.55%	4.83%	1.55%	1.81%	8.45%	5.25%	4.22%	4.72%	11.73%	7.48%
user6	2.85%	1.61%	2.07%	0.49%	4.68%	1.60%	12.34%	17.64%	3.80%	1.61%
user7	0.69%	0.57%	1.39%	0.82%	1.13%	1.09%	16.35%	17.92%	1.27%	0.81%
user8	3.14%	0.53%	1.58%	0.37%	4.36%	0.33%	13.93%	5.40%	6.59%	0.00%
user9	1.66%	2.81%	1.26%	0.59%	3.74%	3.02%	12.24%	9.71%	3.92%	3.32%
user10	4.04%	3.98%	2.85%	1.54%	2.61%	1.80%	11.42%	4.90%	3.95%	4.13%
user11	1.66%	1.07%	0.97%	0.65%	1.69%	0.94%	4.25%	5.68%	3.09%	0.76%
Average	2.90%	1.96%	1.46%	0.81%	3.53%	2.03%	9.34%	8.05%	4.15%	2.11%
Ave. Difference	0.94%		0.64%		1.49%		1.29%		2.03%	
StDev.	2.09%	1.40%	0.70%	0.48%	2.05%	1.83%	4.25%	5.08%	3.03%	2.14%
T-test Paired	0.071871		0.004858		0.010801		0.32726		0.010582	

APDF# Device Group	APDF95 without MidTrap	APDF95 with MidTrap	APDF95 without LatTri	APDF95 with LatTri	APDF95 without UppTrap	APDF95 with UppTrap	APDF95 without ForExt	APDF95 with ForExt	APDF95 without SupSpin	APDF95 with SupSpin
user1	1.19%	1.85%	0.77%	0.56%	7.80%	8.78%	11.63%	10.25%	1.47%	1.91%
user2	4.57%	2.14%	1.01%	0.59%	3.27%	2.16%	12.08%	12.44%	6.03%	3.59%
user3	4.83%	7.43%	3.61%	1.91%	3.58%	1.10%	22.55%	10.84%	4.31%	1.80%
user4	10.16%	3.85%	1.32%	1.42%	6.89%	1.58%	7.54%	7.46%	9.07%	3.70%
user5	13.88%	9.79%	2.46%	4.17%	15.07%	9.76%	6.48%	7.32%	19.80%	13.07%
user6	7.15%	4.07%	3.31%	0.68%	8.25%	3.78%	19.32%	29.11%	7.07%	3.43%
user7	1.18%	1.10%	2.15%	1.25%	1.69%	1.68%	27.72%	28.99%	2.10%	1.42%
user8	6.44%	2.10%	2.28%	1.64%	7.32%	0.57%	23.70%	15.19%	10.63%	0.36%
user9	2.78%	4.69%	2.09%	0.77%	6.45%	7.26%	18.19%	14.57%	6.82%	8.94%
user10	6.84%	6.75%	4.53%	2.57%	4.58%	3.01%	18.31%	8.97%	6.33%	7.00%
user11	2.56%	1.77%	1.38%	1.41%	3.43%	1.32%	9.93%	12.13%	5.41%	2.18%
Average	5.60%	4.14%	2.26%	1.54%	6.21%	3.73%	16.13%	14.30%	7.18%	4.31%
Ave. Difference	1.46%		0.72%		2.48%		1.84%		2.88%	
StDev.	3.90%	2.80%	1.17%	1.07%	3.65%	3.30%	7.03%	7.72%	4.97%	3.84%
T-test Paired	0.115855		0.070919		0.010936		0.345235		0.02459	

Data Summary for Task 13-14, Standing Arm Sweeping

APDF#	APDF10	APDF10	APDF10	APDF10	APDF10	APDF10	APDF10	APDF10	APDF10	APDF10
Device	without	with	without	with	without	with	without	with	without	with
Group	MidTrap	MidTrap	LatTri	LatTri	UppTrap	UppTrap	ForExt	ForExt	SupSpin	SupSpin
user1	0.66%	0.62%	0.46%	0.21%	1.36%	0.00%	6.88%	6.06%	0.99%	0.88%
user2	0.93%	1.06%	0.67%	0.46%	2.33%	1.48%	3.06%	3.83%	1.31%	1.44%
user3	1.09%	0.61%	2.22%	1.19%	0.47%	0.46%	9.26%	8.49%	0.77%	0.79%
user4	3.00%	0.71%	0.89%	0.50%	1.41%	0.84%	4.34%	3.80%	4.47%	1.35%
user5	5.05%	0.65%	1.40%	1.68%	3.66%	0.64%	5.94%	3.50%	6.55%	1.80%
user6	0.65%	0.23%	1.00%	0.43%	0.85%	0.11%	11.59%	4.57%	1.18%	0.52%
user7	0.37%	0.41%	1.12%	0.88%	0.66%	0.82%	14.38%	8.85%	1.23%	1.05%
user8	1.02%	0.36%	1.41%	0.37%	1.04%	0.50%	8.07%	2.92%	1.91%	0.29%
user9	1.73%	1.03%	0.82%	0.72%	0.66%	0.00%	9.58%	9.83%	1.74%	0.14%
user10	2.38%	1.81%	2.30%	1.15%	0.86%	1.42%	9.68%	6.69%	2.21%	0.65%
user11	1.20%	1.19%	1.16%	0.60%	1.08%	0.00%	2.85%	2.92%	1.59%	1.40%
Average	1.64%	0.79%	1.22%	0.74%	1.31%	0.57%	7.79%	5.59%	2.18%	0.94%
Ave. Difference	0.85%		0.48%		0.74%		2.20%		1.24%	
StDev.	1.38%	0.45%	0.59%	0.44%	0.93%	0.54%	3.60%	2.54%	1.76%	0.52%
T-test Paired	0.062399		0.005109		0.026323		0.020576		0.023005	

APDF#	APDF50	APDF50	APDF50	APDF50	APDF50	APDF50	APDF50	APDF50	APDF50	APDF50
Device	without	with	without	with	without	with	without	with	without	with
Group	MidTrap	MidTrap	LatTri	LatTri	UppTrap	UppTrap	ForExt	ForExt	SupSpin	SupSpin
user1	1.08%	1.39%	1.04%	0.65%	4.51%	5.43%	10.32%	9.38%	1.72%	1.58%
user2	1.51%	1.49%	1.18%	0.64%	3.46%	1.89%	4.29%	5.60%	4.35%	2.47%
user3	1.89%	1.23%	3.24%	1.89%	0.64%	0.58%	13.91%	11.76%	1.92%	1.39%
user4	5.88%	2.39%	1.44%	2.17%	4.29%	1.16%	6.09%	5.10%	6.88%	2.65%
user5	10.33%	2.32%	2.27%	3.56%	8.96%	1.33%	8.41%	5.87%	12.30%	3.88%
user6	1.48%	0.37%	2.76%	0.72%	1.64%	0.27%	17.28%	10.85%	2.48%	0.86%
user7	0.60%	2.10%	1.64%	1.22%	0.93%	2.31%	20.28%	14.07%	2.57%	3.10%
user8	1.60%	1.82%	2.02%	0.74%	2.08%	0.76%	11.34%	5.01%	3.74%	0.72%
user9	3.92%	3.26%	1.58%	1.26%	5.82%	1.99%	13.47%	13.40%	8.65%	4.01%
user10	3.53%	4.76%	3.56%	1.89%	2.12%	3.46%	13.24%	10.07%	3.53%	5.02%
user11	1.60%	3.23%	1.54%	0.81%	1.39%	2.98%	5.15%	5.34%	2.51%	4.66%
Average	3.04%	2.21%	2.02%	1.41%	3.26%	2.01%	11.25%	8.77%	4.60%	2.76%
Ave. Difference	0.82%		0.61%		1.25%		2.48%		1.84%	
StDev.	2.87%	1.20%	0.84%	0.90%	2.51%	1.51%	5.05%	3.50%	3.34%	1.51%
T-test Paired	0.350252		0.067189		0.171891		0.01399		0.076019	

APDF#	APDF95	APDF95	APDF95	APDF95	APDF95	APDF95	APDF95	APDF95	APDF95	APDF95
Device	without	with	without	with	without	with	without	with	without	with
Group	MidTrap	MidTrap	LatTri	LatTri	UppTrap	UppTrap	ForExt	ForExt	SupSpin	SupSpin
user1	1.86%	4.86%	2.49%	2.32%	10.01%	13.51%	16.19%	16.16%	3.06%	4.78%
user2	2.47%	2.69%	2.05%	1.10%	6.05%	2.68%	6.68%	9.86%	8.93%	5.68%
user3	3.23%	6.44%	5.47%	5.46%	1.02%	0.88%	22.12%	18.36%	3.54%	2.88%
user4	12.41%	13.29%	3.32%	7.03%	9.29%	3.20%	9.70%	7.78%	11.68%	9.09%
user5	19.72%	10.22%	4.46%	7.51%	21.92%	4.02%	13.04%	10.81%	24.42%	10.38%
user6	2.88%	1.28%	6.21%	2.95%	4.40%	0.63%	27.82%	24.20%	4.07%	1.76%
user7	1.52%	8.27%	2.60%	2.03%	1.56%	9.23%	32.54%	24.96%	4.49%	12.43%
user8	2.94%	3.93%	3.13%	2.33%	3.57%	1.65%	16.78%	10.14%	6.07%	1.67%
user9	6.83%	9.85%	3.07%	3.04%	14.17%	9.10%	20.85%	19.96%	16.43%	11.88%
user10	5.94%	10.39%	6.03%	4.05%	4.64%	7.92%	19.80%	15.90%	6.48%	12.81%
user11	2.37%	7.97%	2.37%	1.61%	1.92%	10.52%	11.23%	12.38%	3.81%	13.59%
Average	5.65%	7.20%	3.75%	3.58%	7.14%	5.76%	17.89%	15.50%	8.45%	7.90%
Ave. Difference	-1.55%		0.16%		1.38%		2.39%		0.55%	
StDev.	5.64%	3.71%	1.53%	2.18%	6.36%	4.43%	7.80%	5.88%	6.70%	4.66%
T-test Paired	0.270648		0.79217		0.549097		0.0328		0.79301	

Data Summary for Task 15-16, Standing Reaching

Device Group	without MidTrap	with MidTrap	without LatTri	with LatTri	without UppTrap	with UppTrap	without ForExt	with ForExt	without SupSpin	with SupSpin
user1	1.37%	0.58%	1.42%	1.08%	2.67%	1.58%	15.29%	15.25%	2.56%	1.02%
user2	1.62%	1.36%	1.73%	1.08%	6.21%	2.43%	19.14%	13.85%	3.18%	1.90%
user3	1.54%	2.33%	4.54%	2.77%	0.00%	0.11%	28.41%	27.03%	1.37%	1.83%
user4	1.84%	1.11%	1.38%	1.11%	2.88%	0.88%	11.19%	11.69%	3.99%	2.02%
user5	2.52%	3.03%	2.20%	1.59%	1.37%	2.13%	10.49%	4.38%	3.59%	3.09%
user6	1.59%	0.70%	3.22%	1.69%	1.23%	0.80%	16.43%	18.15%	3.15%	1.95%
user7	1.39%	1.13%	2.32%	1.89%	1.46%	6.24%	32.10%	32.90%	4.90%	4.61%
user8	2.31%	0.86%	3.11%	2.02%	2.38%	0.45%	18.36%	19.42%	5.04%	0.49%
user9	3.17%	2.95%	2.54%	1.98%	0.78%	1.50%	12.27%	16.33%	4.63%	5.75%
user10	2.75%	2.64%	3.14%	2.79%	2.83%	2.86%	9.60%	18.95%	2.78%	2.86%
user11	2.00%	1.67%	1.66%	1.32%	0.84%	0.96%	2.66%	5.23%	3.70%	2.65%
Average	2.01%	1.67%	2.48%	1.76%	2.06%	1.81%	15.99%	16.65%	3.54%	2.56%
Ave. Difference	0.34%		0.72%		0.25%		-0.66%		0.97%	
StDev.	0.60%	0.92%	0.97%	0.62%	1.67%	1.69%	-8.46%	-8.38%	1.10%	1.52%
T-test Paired	0.105294		0.000925		0.712984		0.615664		0.056845	

APDF# Device Group	APDF50 without MidTrap	APDF50 with MidTrap	APDF50 without LatTri	APDF50 with LatTri	APDF50 without UppTrap	APDF50 with UppTrap	APDF50 without ForExt	APDF50 with ForExt	APDF50 without SupSpin	APDF50 with SupSpin
user1	1.99%	1.17%	1.92%	1.56%	6.36%	5.52%	23.87%	24.25%	3.64%	1.60%
user2	2.09%	1.74%	2.32%	1.46%	8.40%	3.14%	26.05%	19.71%	4.53%	2.82%
user3	3.11%	3.84%	6.68%	3.90%	0.25%	1.11%	42.53%	42.30%	2.54%	3.13%
user4	2.80%	1.76%	1.82%	1.50%	5.13%	1.19%	18.59%	19.50%	6.01%	3.80%
user5	4.23%	6.44%	3.10%	2.35%	2.48%	3.62%	15.48%	7.16%	5.10%	6.23%
user6	2.47%	1.13%	4.46%	2.37%	1.81%	1.11%	23.49%	25.37%	4.41%	2.93%
user7	2.51%	3.10%	3.29%	2.53%	2.59%	10.98%	49.84%	55.89%	7.14%	8.01%
user8	3.91%	1.81%	4.86%	2.80%	4.50%	1.08%	40.97%	35.36%	8.17%	2.18%
user9	4.73%	5.15%	3.56%	2.84%	2.94%	7.47%	17.81%	25.42%	8.84%	10.62%
user10	4.07%	4.35%	4.67%	3.81%	4.43%	5.32%	15.23%	31.12%	4.03%	5.17%
user11	2.82%	2.34%	2.25%	1.80%	1.29%	1.37%	7.94%	10.16%	5.27%	4.54%
Average	3.16%	2.99%	3.54%	2.45%	3.65%	3.81%	25.62%	26.93%	5.42%	4.64%
Ave. Difference	0.17%		1.09%		-0.16%		-1.31%		0.78%	
StDev.	0.93%	1.76%	1.51%	0.86%	2.39%	3.24%	-13.23%	-13.98%	1.95%	2.73%
T-test Paired	0.640725		0.001369		0.895757		0.543552		0.274812	

APDF# Device Group	APDF95 without MidTrap	APDF95 with MidTrap	APDF95 without LatTri	APDF95 with LatTri	APDF95 without UppTrap	APDF95 with UppTrap	APDF95 without ForExt	APDF95 with ForExt	APDF95 without SupSpin	APDF95 with SupSpin
user1	3.34%	4.74%	3.07%	2.61%	13.87%	13.99%	40.69%	39.50%	5.99%	4.31%
user2	3.05%	2.56%	3.52%	2.18%	12.73%	4.53%	38.87%	30.56%	7.39%	4.41%
user3	8.23%	6.86%	11.81%	6.62%	1.82%	7.59%	70.02%	77.89%	6.81%	8.41%
user4	5.15%	3.93%	2.77%	2.30%	9.16%	1.93%	30.18%	31.62%	9.92%	7.45%
user5	7.55%	13.02%	5.00%	3.91%	4.69%	6.75%	25.60%	12.00%	7.77%	11.99%
user6	5.01%	3.04%	6.81%	3.72%	4.50%	1.86%	37.67%	38.21%	6.74%	4.68%
user7	6.33%	7.04%	5.21%	3.79%	6.23%	18.57%	83.07%	102.18%	11.38%	13.79%
user8	7.07%	4.02%	7.90%	4.45%	8.97%	4.08%	69.35%	73.20%	14.36%	6.09%
user9	7.82%	11.72%	5.68%	4.74%	10.51%	21.39%	30.03%	42.51%	16.17%	24.58%
user10	7.05%	7.85%	7.85%	5.96%	7.66%	9.52%	26.56%	52.29%	6.69%	9.57%
user11	4.44%	3.65%	3.55%	2.93%	2.67%	2.31%	18.66%	22.02%	8.07%	7.35%
Average	5.91%	6.22%	5.74%	3.93%	7.53%	8.41%	42.79%	47.45%	9.21%	9.33%
Ave. Difference	-0.31%		1.82%		-0.88%		-4.66%		-0.12%	
StDev.	1.81%	3.50%	2.71%	1.44%	3.95%	6.81%	-21.40%	-26.87%	3.40%	5.91%
T-test Paired	0.696378		0.002438		0.673444		0.203201		0.930319	

Data Summary for Task 17-18, Standing Drilling

APDF#	APDF10	APDF10	APDF10	APDF10	APDF10	APDF10	APDF10	APDF10	APDF10	APDF10
Device	without	with	without	with	without	with	without	with	without	with
Group	MidTrap	MidTrap	LatTri	LatTri	UppTrap	UppTrap	ForExt	ForExt	SupSpin	SupSpin
user1										
user2										
user3										
user4	2.11%	1.01%	1.61%	0.56%	3.30%	0.69%	2.72%	2.91%	3.55%	1.08%
user5	1.39%	2.06%	1.89%	1.54%	1.97%	4.63%	5.63%	2.53%	3.88%	4.71%
user6	1.17%	0.24%	2.30%	0.79%	2.40%	0.41%	13.47%	12.34%	2.09%	0.59%
user7	0.91%	1.27%	1.06%	0.51%	1.03%	4.58%	15.81%	13.69%	3.16%	2.37%
user8	1.35%	0.54%	1.19%	0.42%	3.91%	0.55%	9.64%	0.78%	5.12%	0.85%
user9	4.22%	0.97%	1.71%	0.50%	7.06%	0.74%	10.95%	7.45%	9.62%	0.52%
user10	3.37%	0.96%	1.86%	0.66%	3.14%	0.48%	10.19%	10.33%	4.02%	0.65%
user11	1.87%	1.30%	0.90%	0.58%	1.93%	1.33%	2.27%	1.93%	2.16%	1.01%
Average	2.05%	1.04%	1.57%	0.70%	3.09%	1.68%	8.83%	6.50%	4.20%	1.47%
Ave. Difference	1.00%		0.87%		1.42%		2.34%		2.73%	
StDev.	1.16%	0.54%	0.48%	0.36%	1.85%	1.83%	4.90%	5.12%	2.40%	1.43%
T-test Paired	0.065482		0.000826		0.255506		0.062383		0.037881	

APDF#	APDF50	APDF50	APDF50	APDF50	APDF50	APDF50	APDF50	APDF50	APDF50	APDF50
Device	without	with	without	with	without	with	without	with	without	with
Group	MidTrap	MidTrap	LatTri	LatTri	UppTrap	UppTrap	ForExt	ForExt	SupSpin	SupSpin
user1										
user2										
user3										
user4	2.81%	1.30%	2.16%	0.65%	5.80%	0.85%	3.50%	3.80%	4.62%	1.48%
user5	1.88%	3.04%	2.55%	2.42%	3.39%	7.14%	7.85%	3.67%	4.93%	6.95%
user6	1.66%	0.32%	3.01%	1.09%	3.31%	0.55%	17.76%	16.98%	2.63%	0.76%
user7	1.21%	3.00%	1.38%	0.62%	1.30%	8.40%	21.51%	21.55%	3.92%	6.81%
user8	1.98%	0.83%	1.54%	0.53%	5.73%	0.82%	13.63%	1.72%	7.38%	1.44%
user9	5.59%	1.19%	2.32%	0.56%	9.83%	0.90%	14.76%	10.31%	12.94%	0.62%
user10	4.47%	1.20%	2.47%	0.84%	4.48%	0.58%	13.58%	13.58%	5.56%	0.80%
user11	2.20%	1.50%	1.09%	0.64%	2.10%	1.44%	3.75%	3.24%	2.66%	1.28%
Average	2.72%	1.55%	2.07%	0.92%	4.49%	2.58%	12.04%	9.36%	5.58%	2.52%
Ave. Difference	1.18%		1.15%		1.91%		2.69%		3.06%	
StDev.	1.52%	0.98%	0.66%	0.64%	2.68%	3.23%	6.48%	7.41%	3.35%	2.71%
T-test Paired	0.148206		0.001705		0.330975		0.11177		0.115365	

APDF#	APDF95	APDF95	APDF95	APDF95	APDF95	APDF95	APDF95	APDF95	APDF95	APDF95
Device	without	with	without	with	without	with	without	with	without	with
Group	MidTrap	MidTrap	LatTri	LatTri	UppTrap	UppTrap	ForExt	ForExt	SupSpin	SupSpin
user1										
user2										
user3										
user4	4.26%	3.22%	3.27%	0.80%	10.14%	1.21%	5.16%	5.68%	6.55%	2.28%
user5	3.10%	4.91%	3.76%	4.77%	5.49%	11.51%	12.18%	8.25%	6.72%	10.69%
user6	2.69%	1.28%	4.33%	1.73%	5.11%	0.86%	25.57%	28.13%	3.58%	1.23%
user7	1.82%	5.50%	2.02%	0.86%	1.96%	14.05%	33.33%	36.43%	5.25%	11.34%
user8	3.32%	1.65%	2.25%	0.76%	9.43%	1.36%	20.15%	5.64%	11.86%	2.49%
user9	8.17%	1.57%	3.83%	0.61%	15.47%	1.34%	21.80%	15.81%	19.42%	0.79%
user10	6.73%	2.27%	3.70%	1.23%	7.05%	1.24%	20.18%	19.72%	8.56%	1.21%
user11	2.75%	1.98%	1.55%	0.74%	2.34%	1.61%	6.65%	7.31%	3.60%	1.79%
Average	4.11%	2.80%	3.09%	1.44%	7.12%	4.15%	18.13%	15.87%	8.19%	3.98%
Ave. Difference	1.31%		1.65%		2.98%		2.26%		4.22%	
StDev.	2.21%	1.60%	1.01%	1.39%	4.48%	5.37%	9.59%	11.51%	5.29%	4.38%
T-test Paired	0.289847		0.010513		0.355835		0.310293		0.170561	

Data Summary for Task 19-20, Standing Arms Extended

Appendix B: Command Chair Study (Chapter 4) Support Documents

This appendix includes the documentation and Committee for the Protection of Human Subjects (CPHS) approval letter for the Command Chair study described in Chapter 4. These documents provide the specific procedural details for this set of experiments as provided to CPHS. The subjective questionnaires used in this study are also provided.

B.1 Test Protocol

INVESTIGATOR:
Mr. Daniel L. Odell, Graduate Student
Department of Mechanical Engineering

FACULTY ADVISOR:
Prof. Paul Wright, Ph.D.
Department of Mechanical Engineering

1. TITLE: "Two-Dimensional Fitts' Tapping Test"

2. RELATED PROJECTS: This project is a follow-up to CPHS#2003-3-37, "One-Dimensional Fitts' Tapping Test."

3. NATURE AND PURPOSE: The objective of this study is to determine how the throughput, learning rate, and error rate of a new computer input device (the "Command Chair") compare to those of a standard mouse. In addition, measures of comfort of the new device will be taken through the use of post-test subjective questionnaires, and the measurement of wrist extension. The Command Chair is similar to a mouse, but sits on the armrest of a chair – potentially providing ergonomic benefits. These measurements will be made by using freely available software (GFLMB), which records the time required for a user to tap between targets on a computer screen.

Fig 1., The Command Chair

4. SUBJECTS: Ten to fourteen computer-literate subjects will be recruited from the Department of Mechanical Engineering. All proposed subjects will be over 18 years of age.

5. RECRUITMENT: Subjects will be solicited from Prof. Wright's weekly seminar. The details of the study will be announced during the first 5 minutes of the seminar, and screening questionnaires will be handed out to interested individuals.

The following statement will be made at the beginning of class: "Hello everybody. My name is Dan Odell, and I am a 5th year student in Mechanical Engineering. I am currently preparing to run an experiment to determine the pointing speed of a new type of computer pointing device. I'm looking for 10-14 volunteers to help me test the device. The experiment will require roughly 1½ hours of time. So, if you're interested in participating in an exciting experiment and checking out a new type of computer pointing device, please raise your hand and I'll give you a screening questionnaire. I'll collect the forms at the end of class. Thank you."

Consent forms will be distributed, signed, and collected at the beginning of the testing session, before instruction packages are issued and testing begins.

6. SCREENING PROCEDURES: Ten to fourteen right-handed subjects who use a computer with a mouse on a daily basis will be selected. Computer users with more experience, and who use more pointing-based applications are considered to be more desirable. In addition, potential subjects with any upper body injuries (particularly repetitive strain injuries) or disabilities will be disqualified from the study, as these afflictions may affect their subjective opinions on the effort required to operate the device, and the fatigue resulting from its use. All screening questionnaires for subjects screened out of the study will be destroyed.

7. PROCEDURES: Subjects will be asked to:

1) Learn how to use the Command Chair (~5 minutes).
2) Practice pointing with it until they reach a reasonable level of skill (~10 minutes).
3) Wear a wrist goniometer to measure wrist extension during mousing.
4) Perform a simple pointing and timing study by performing a pointing task (clicking between targets on a computer screen) using the Command Chair (~25 minutes).
5) Repeat the study using a standard mouse (~25 minutes).
6) Repeat the study using a mouse with fixed forearm support. (~25 minutes).
7) Answer a questionnaire about using the Command Chair (~10 minutes).

The order of steps 4 to 6 will be randomized in order to randomize any task-learning effects. The total task time is expected to be 1.75 hours per subject. Participants will be given a short break (~2 mins.) between each task. In addition, subjects may take a break anytime they desire after every trial block.

The wrist goniometer is a flexible measurement device roughly 5” long and ½” wide that measures wrist extension. It attaches to a participant’s wrist with skin tape.

All tests will be performed in the Berkeley Manufacturing Institute Design Studio in 2111 Etcheverry hall. Device tests will be performed consecutively, in a single 1.75 hour session. Subjects will not be photographed or videotaped for this test.

The tapping test follows the standard set in ISO 9241-9, *Ergonomic requirements for office work with visual display terminals (VDTs) – Requirements for non-keyboard input devices.*

8. BENEFITS: There are no foreseeable direct benefits to the subjects. However, the study will provide valuable information about the nature of computer pointing devices, which may lead to improved designs in the future.

9. RISKS: There are no known risks for subjects performing this experiment.

10. CONFIDENTIALITY: Subjects will be issued code numbers upon acceptance to the study. When compiling data, subjects will be referred to only by code number. At the conclusion of the test, the screening questionnaires, which identify participants, will be destroyed. During the study, screening questionnaires will be stored separately from testing data.

11. INFORMED CONSENT: The subjects will be given the consent documents to read and sign at the initial meeting, after the screening process.

12. FINANCIAL ASPECTS: None.

13. WRITTEN MATERIALS: Please find attached a copy of the post-test questionnaire, the screening questionnaire, and the testing instruction set.

B.2 Screening Questionnaire

Name:____
Phone: ___________________________ Hours at this phone: ____________
Address:____

Computer System Familiarity

1. Which computer systems do you use? (please check appropriate box)

	Rarely used	Use once a week	Use daily
PC	o	o	o
Macintosh	o	o	o
Unix	o	o	o

2. How many years have you used a computer?

3. What are your principle uses for a computer?

4. How familiar are you with the following? (please check appropriate box)

	Rarely used	Use once a week	Use daily
Computer Mouse	o	o	o
Trackball	o	o	o
Joystick	o	o	o
Touchpad	o	o	o

Physical Performance

1. Are you right – or left-handed?
2. Have you ever had repetitive strain injury (RSI) or carpel tunnel syndrome with any limb? Please Describe.

3. Do you have any problems using your hand? This includes soreness or disability. If so, please describe.

4. Roughly how many words per minute can you type? Are you a touch-typist?

5. How tall are you? What is your age?

6. Do you usually plant your wrist while mousing?

7. When are you available for 2.5 consecutive hours?

This form will be destroyed for subjects not selected for testing participation.

B.3 Informed Consent Form

My name is Dan Odell, and I am a graduate student in the Mechanical Engineering Department at the University of California at Berkeley. I am currently performing a study to examine the pointing properties of a new computer input device – the Command Chair. For the purposes of this research, I am asking people to perform the following tasks:

1) Learn how to use the Command Chair (~5 minutes).
2) Practice pointing with it until achieving a reasonable level of skill (~10 minutes).
3) Wear a wrist goniometer to measure wrist extension during mousing.
4) Perform a simple pointing and timing study by performing a simple pointing task (clicking between rectangles on a computer screen) using the Command Chair (~25 minutes).
5) Repeat the study using a standard mouse (~25 minutes).
6) Repeat the study using a mouse with fixed forearm support. (~25 minutes).
7) Answer a questionnaire about using the Command Chair (~10 minutes).

There will be a break between each task. The total task time will be approximately 1 hour and 45 minutes. The wrist goniometer will be attached with skin tape and calibrated prior to testing. Any information that is obtained in connection with this study that can be identified with volunteers will remain confidential and will be disclosed only with their written permission. The Screening Questionnaire that subjects have filled out will be destroyed at the end of the study. Computer data and Post-test Questionnaires will be kept, but will be identified only by a code number. There will be no means of linking subject's names to the number.
During the course of the study, if you find the task too fatiguing, or if you feel eyestrain, you can pause for a break. Your participation is entirely voluntary, and you can discontinue your participation at any time.

There are no known risks to subjects from taking part in this research, and no direct benefits either. However, it is hoped that the research will benefit researchers with better understanding of human-computer interfacing.

If you have any questions about the research, you can call me, the director of the research study, Dan Odell, at 643-6546, or contact me at dano@kingkong.me.berkeley.edu.
Your signature below indicates that you have read and understood the information provided above, that you willingly agree to participate, that you consent to the use of data gathered during the course of this study and through the screening questionnaire, and that you may withdraw your consent at any time and discontinue participation at any time, and that you will receive a copy of this form upon request. If you have any question regarding your treatment or rights as a participant in this research project, please contact the University of California at Berkeley's, Committee for Protection of Human Subjects at 510/642-7461, subjects@uclink.berkeley.edu.

I have read this consent form and agree to participate in this research.

Signature ____ Date _________________

B.3 Participant Instruction Set

Command Chair Familiarization
The Command Chair is a new computer input device that consists of a pair of articulating arm rests attached to an office chair. At the end of the rests is a half-keyboard. As the keyboards are moved in the horizontal plane, the keyboard motion provides mouse input.

This experiment will test the pointing capabilities of the Command Chair. This section will help to familiarize you with its function. During these first two sections, try to get a good feel for how to manipulate the pointer quickly and accurately. First, rest your forearms on the armrests and place your index and middle fingers on the red buttons embedded in the keyboard between the characters "H" and "J", and "J" and "K."

Now, click on the Internet Explorer Icon on the taskbar near the bottom left of the screen. The portal "Yahoo.com" will open. Spend about four minutes practicing clicking on the links presented there. Don't worry much about typing anything; the focus here is on the pointer. After roughly four minutes, close Internet Explorer.

At this point, the experimenter will attach the goniomoter to your wrist. A goniometer is a flexible sensor that measures wrist extension. It attaches using skin tape. After attaching and calibrating the goniometer, the practice session will begin.

Practice
Double-click the desktop icon "shortcut to GFLMB," in the center of the screen. This is the application that will be used for testing. Select "R" for "Run Subject." Enter your user ID (e.g. user1) for "subject number", the session number (1), and select "yes" under practice session. You may leave "subject name," and "sitting number" blank. Under data file name, enter "data/(your user ID)/test1" (e.g. data/user1/test1), then click the "start" button.

The interface will present you with a cursor box and a target shape. The test is begun by left-clicking. Before left-clicking, you may pause for a short break, or left-click to initiate the experimental trial. At this pause, you should *always re-center the input device to a centered position*. Upon left-clicking, a cursor will appear in the cursor box. The goal is to left-click the cursor anywhere inside the target shape (aim for the center). Once a click is made, the software will return to the pause screen. If the cursor is clicked outside of the target, the computer will beep to signal an error.

For this practice session, work as fast as possible while still maintaining high accuracy (<10% error). Upon completion of this practice, take a short break.

Chair Test

At this point, the practiced test of the pointing device will begin. Select "Run Subject" (or type "R") under GFLMB. Enter your user ID (e.g. user1) for "subject number", the session number (1), and select "no" under practice session. You may leave "subject name," and "sitting number" blank. Under data file name, enter "data/(your user ID)/chair1" (e.g. data/user1/chair1), then click the "start" button. The session number, and the number following "chair" should be incremented for every following test (e.g. chair2 for session 2).

The interface will present you with a cursor box and a target shape. The test is begun by left-clicking. Before left-clicking, you may pause for a short break, or left-click to initiate the experimental trial. At this pause, you should *always re-center the input device to a centered position*. Upon left-clicking, a cursor will appear in the cursor box. The goal is to left-click the cursor anywhere inside the target shape (aim for the center). Once a click is made, the software will return to the pause screen. If the cursor is clicked outside of the target, the computer will beep to signal an error. *For all tests, work as fast as possible while still maintaining high accuracy (<10% error).* Try to be consistent with your error rate.

Run the chair test 6 times. For the seventh test block, the test software will require you to start the test by pressing the space bar with your right hand. After pressing the space bar, complete the trial as normal.

Finally, the test administrator will run a program that tests device performance for a combined pointing and typing task. For this test, click on the highlighted cell, and type the name of the highlight color. Do not correct your mistakes. Press 'enter' when the color name is complete. Return the cursor to the homing cell (black cell at the center of the screen) and click on it to complete the trial. The next trial will start automatically, and the program will end when testing is complete.

If something extraneous to the test affects your pointing time (such as a sneeze), note the event below. Feel free to take short breaks (~2 minutes) as needed between blocks.

B.4 Post-test Questionnaire

Learning
1) Did you find this device easy to learn? Explain.

2) How would you compare learning the Command Chair to learning a regular mouse?

3) What did find hardest to learn about the Command Chair?

Practiced Skill
4) At the end of the study, did you feel like you could control the Command Chair in all situations? If not, where did you have problems?

5) Did you find the Command Chair comfortable to use? If not, why not?

6) Did you have any fatigue from using the Command Chair? If so, where?

Overall
7) If you could use the Command Chair with your computer, would you? Explain.

8) Would you prefer to use it for certain tasks? Examples: word processing, spreadsheets, video games.

9) Would you like to be able to switch between the hand mouse and the Command Chair?

10) Can you imagine any circumstances in which someone might prefer the Command Chair to a conventional mouse?

11) What did you like about the Command Chair?

12) What did you dislike about the Command Chair?

13) Did you have any trouble moving the cursor to the target? If so, please describe.

14) Did you have any trouble selecting (clicking) a target? If so, please describe.

15) Do you have any suggestions on how to improve this device?

16) How does the device compare to using a mouse with fixed forearm support?

Mouse Effort			**Command Chair Effort**			**Effort**
Arm	**Shoulder**	**Neck**	**Arm**	**Shoulder**	**Neck**	
( ) 10	( ) 10	( ) 10	( ) 10	( ) 10	( ) 10	Very, very strong (almost max.)
( ) 9	( ) 9	( ) 9	( ) 9	( ) 9	( ) 9	
( ) 8	( ) 8	( ) 8	( ) 8	( ) 8	( ) 8	
( ) 7	( ) 7	( ) 7	( ) 7	( ) 7	( ) 7	Very strong
( ) 6	( ) 6	( ) 6	( ) 6	( ) 6	( ) 6	
( ) 5	( ) 5	( ) 5	( ) 5	( ) 5	( ) 5	Strong (heavy)
( ) 4	( ) 4	( ) 4	( ) 4	( ) 4	( ) 4	Somewhat strong
( ) 3	( ) 3	( ) 3	( ) 3	( ) 3	( ) 3	Moderate
( ) 2	( ) 2	( ) 2	( ) 2	( ) 2	( ) 2	Weak (light)
( ) 1	( ) 1	( ) 1	( ) 1	( ) 1	( ) 1	Very weak
( ) .5	( ) .5	( ) .5	( ) .5	( ) .5	( ) .5	Very, very weak (just noticeable)
( ) 0	( ) 0	( ) 0	( ) 0	( ) 0	( ) 0	Nothing at all

Quantitative Device Assessment

Mark the point of the continuum for each question that best describes your experience with each input device (represented by the following codes).

Supported mouse
Unsupported mouse
Chair

1) The force required for actuation was:

S——S
U——U
C——C
0 1 2 3 4 5
low too high

2) Smoothness during operation was:

S——S
U——U
C——C
0 1 2 3 4 5
very smooth very rough

3) The mental effort required for use was:

S——S
U——U
C——C
0 1 2 3 4 5
low too high

4) The physical effort required for use was:

S——S
U——U
C——C
0 1 2 3 4 5
low too high

5) Accurate pointing was:

S——S
U——U
C——C
0 1 2 3 4 5
easy difficult

6) Operation speed was:

S——S
U——U
C——C
0 1 2 3 4 5
too fast too slow

7) Finger fatigue:

S——————————S
U——————————U
C——————————C
0 1 2 3 4 5
none very high

8) Wrist fatigue:

S——————————S
U——————————U
C——————————C
0 1 2 3 4 5
none very high

9) Arm fatigue:

S——————————S
U——————————U
C——————————C
0 1 2 3 4 5
none very high

10) Shoulder fatigue:

S——————————S
U——————————U
C——————————C
0 1 2 3 4 5
none very high

11) Neck fatigue:

S——————————S
U——————————U
C——————————C
0 1 2 3 4 5
none very high

12) General comfort:

S——————————S
U——————————U
C——————————C
0 1 2 3 4 5
comfortable uncomfortable

13) Overall, the use of the device was:

S——————————S
U——————————U
C——————————C
0 1 2 3 4 5
easy difficult

B.5 CPHS Acceptance Letter

BERKELEY: COMMITTEE FOR PROTECTION
OF HUMAN SUBJECTS
101 WHEELER HALL, MC #1340
642-7461 * FAX: 643-6272
subjects@uclink4.berkeley.edu
October 27, 2003

MR. DAN ODELL
Department of Mechanical Engineering
2111 Etcheverry Hall, #1740

Re: “Two-Dimensional Fitts’ Tapping Test” – Graduate Research

The Project referred to above was given an approval in an expedited manner by the Committee for Protection of Human Subjects on Thursday, October 23, 2003.

The number given to this project is 2003-10-44. Please refer to this number in all future correspondence.

The expiration date of this approval is October 16, 2004. Approximately six weeks before the expiration date, we will send you a continuation/renewal request form. Please fill out the form and return it to the Committee, according to the instructions. If you do not receive these forms in a timely manner, please contact the CPHS Office at (510) 642-7461, or visit our website at http://cphs.berkeley.edu.

Attached is a copy of the consent materials reviewed by the Committee; the expiration date of the Committee's review of this form is noted on it. Please copy and use this stamped consent form for the coming year.

Please note that even though the Committee has approved your project, you must bring promptly to our attention any changes in the design or conduct of your research that affect human subjects. If any of your subjects experience any untoward events in the course of this research, you must inform the Committee within ten (10) working days.

If you have any questions regarding this matter, please contact the CPHS staff at 642-7467, FAX 643-6272, e-mail: adelphia@uclink4.berkeley.edu.

Sincerely,

Jane Gilbert Mauldon
Chair, Committee for Protection of Human Subjects
Associate Professor, Goldman School of Public Policy

cc: Professor Paul Wright
Graduate Division (SID #11226113)

JGM:amb

UNIVERSITY OF CALIFORNIA (Letterhead for Interdepartmental Use)

B.6 Raw Pointing Data

Mouse user1

LN Block	Block#	Mean Move	Ave. Thrup	Ttest time	Error	Error%
0	1	1468	3.14	0.034294	5	6.94%
0.693147	2	1578	3.14	0.514472	2	2.78%
1.098612	3	1617	3.13	0.890831	2	2.78%
1.386294	4	1611	3.16	0.730773	2	2.78%
1.609438	5	1602	2.95	0.101315	3	4.17%
1.791759	6	1501	3.26		4	5.56%
Averages		1563	3.13		3	4.17%
StDev		63.0554	0.10		1.264911	1.76%
Practiced Performace:	Block 6 only			Homing Time		
Averages		1501	3.26	563.9444	4	5.56%
StDev		333	0.36	81.51849		
Learning %		2.21%	3.96%			

Command Chair

LN Block	Block#	Mean Move	Ave. Thrup	Ttest time	Error	Error%
0	1	2497	1.83	0.287315	7	9.72%
0.693147	2	2433	1.40	0.052298	10	13.89%
1.098612	3	2172	1.80	0.106375	4	5.56%
1.386294	4	2400	1.71	0.029817	8	11.11%
1.609438	5	2140	2.09	0.085281	6	8.33%
1.791759	6	2470	1.78		7	9.72%
Averages		2352	1.77		7	9.72%
StDev		155.7892	0.22		2	2.78%
Practiced Performace:	Block 6 only			Homing Time		
Averages		2470	1.78	55.23611	7	9.72%
StDev		908	0.30	51.69616		
Learning %		1.10%	2.45%			

Mouse with Forearm Support

LN Block	Block#	Mean Move	Ave. Thrup	Ttest time	Error	Error%
0	1	1673	2.86	0.668023	3	4.17%
0.693147	2	1707	2.95	0.310483	1	1.39%
1.098612	3	1781	2.90	0.063	2	2.78%
1.386294	4	1667	3.07	0.104642	2	2.78%
1.609438	5	1573	3.21	0.694313	3	4.17%
1.791759	6	1554	3.25		2	2.78%
Averages		1659	3.04		2	3.01%
StDev		84.68326	0.16		0.752773	1.05%
Practiced Performace:	Block 6 only			Homing Time		
Averages		1554	3.25	648.75	2	2.78%
StDev		345	0.39	96.4131		
Learning %		7.10%	13.50%			

Mouse user2

LN Block	Block#	Mean Move	Ave. Thrup	Ttest time	Error	Error%
0	1	1492	3.26	0.477197	2	2.78%
0.693147	2	1414	3.28	0.138588	2	2.78%
1.098612	3	1532	3.22	0.559382	1	1.39%
1.386294	4	1506	3.41	0.122958	0	0.00%
1.609438	5	1376	3.54	0.026496	0	0.00%
1.791759	6	1262	3.76		2	2.78%
Averages		1430	3.41		1	1.62%
StDev		101.4065	0.21		0.983192	1.37%
Practiced Performace:	Block 6 only			Homing Time		
Averages		1262	3.76	720.7222	2	2.78%
StDev		412	0.55	100.6892		
Learning %		15.44%	15.34%			

Command Chair

LN Block	Block#	Mean Move	Ave. Thrup	Ttest time	Error	Error%
0	1	2240	1.79	0.09385	9	12.50%
0.693147	2	2568	1.64	0.821442	9	12.50%
1.098612	3	2515	1.61	0.558439	9	12.50%
1.386294	4	2660	1.58	0.642454	7	9.72%
1.609438	5	2631	1.59	0.029829	6	8.33%
1.791759	6	2196	1.92		7	9.72%
Averages		2468	1.69		8	10.88%
StDev		200.4647	0.14		1.32916	1.85%
Practiced Performace:	Block 6 only			Homing Time		
Averages		2196	1.92	83.51389	7	9.72%
StDev		939	0.37	87.53559		
Learning %		1.97%	7.37%			

Mouse with Forearm Support

LN Block	Block#	Mean Move	Ave. Thrup	Ttest time	Error	Error%
0	1	1444	3.37	0.029432	0	0.00%
0.693147	2	1314	3.61	0.010086	1	1.39%
1.098612	3	1464	3.28	0.0078	0	0.00%
1.386294	4	1678	2.98	0.00096	0	0.00%
1.609438	5	1387	3.29	0.320439	4	5.56%
1.791759	6	1419	3.36		2	2.78%
Averages		1451	3.31		1	1.62%
StDev		123.1008	0.20		1.602082	2.23%
Practiced Performace:	Block 6 only			Homing Time		
Averages		1419	3.36	691.125	2	2.78%
StDev		446	0.46	119.5416		
Learning %		1.79%	0.27%			

Mouse — user3

LN Block	Block#	Mean Mov	Ave. Thrup	Ttest time	Error	Error%
0	1	1330	3.32	0.442051	2	2.78%
0.693147	2	1347	3.21	0.291975	3	4.17%
1.098612	3	1312	3.48	0.089483	0	0.00%
1.386294	4	1233	2.62	0.19323	2	2.78%
1.609438	5	1308	3.77	0.27359	2	2.78%
1.791759	6	1253	3.65		1	1.39%
Averages		1297	3.34		2	2.31%
StDev		44.93647	0.41		1.032796	1.43%
Practiced Performace:	Block 6 only			Homing Time		
Averages		1253	3.65	593.25	1	1.39%
StDev		370	0.36	110.2689		
Learning %		5.84%	9.76%			

Mouse — user4

LN Block	Block#	Mean Mov	Ave. Thrup	Ttest time	Error	Error%
0	1	1949	1.67	0.404523	5	6.94%
0.693147	2	1865	2.62	0.003351	2	2.78%
1.098612	3	1657	2.88	0.052295	1	1.39%
1.386294	4	1721	2.57	0.000946	3	4.17%
1.609438	5	1911	2.51	0.000987	1	1.39%
1.791759	6	1661	2.79		0	0.00%
Averages		1794	2.51		2	2.78%
StDev		130.3422	0.43		1.788854	2.48%
Practiced Performace:	Block 6 only			Homing Time		
Averages		1661	2.79	617.4444	0	0.00%
StDev		621	0.19	131.2828		
Learning %		14.81%	66.74%			

Command Chair — user3

LN Block	Block#	Mean Mov	Ave. Thrup	Ttest time	Error	Error%
0	1	2285	1.77	0.050393	8	11.11%
0.693147	2	2107	1.96	0.500471	3	4.17%
1.098612	3	2054	1.99	0.385887	4	5.56%
1.386294	4	1921	2.10	0.414604	10	13.89%
1.609438	5	2055	1.93	0.321178	11	15.28%
1.791759	6	1902	2.13		7	9.72%
Averages		2054	1.98		7	9.95%
StDev		139.0478	0.13		3.188521	4.43%
Practiced Performace:	Block 6 only			Homing Time		
Averages		1902	2.13	32.63889	7	9.72%
StDev		670	0.31	49.72695		
Learning %		16.74%	20.54%			

Command Chair — user4

LN Block	Block#	Mean Mov	Ave. Thrup	Ttest time	Error	Error%
0	1	2772	1.53	0.016911	5	6.94%
0.693147	2	2308	1.62	0.419941	13	18.06%
1.098612	3	2547	1.41	0.989869	12	16.67%
1.386294	4	2533	1.40	0.462473	13	18.06%
1.609438	5	2501	1.65	0.035686	8	11.11%
1.791759	6	2187	1.88		7	9.72%
Averages		2475	1.58		10	13.43%
StDev		204.0722	0.18		3.444803	4.78%
Practiced Performace:	Block 6 only			Homing Time		
Averages		2187	1.88	62.70833	7	9.72%
StDev		959	0.22	53.48356		
Learning %		21.09%	23.35%			

Mouse with Forearm Support — user3

LN Block	Block#	Mean Mov	Ave. Thrup	Ttest time	Error	Error%
0	1	1020	3.99	0.265423	7	9.72%
0.693147	2	998	4.12	0.036638	6	8.33%
1.098612	3	1088	3.85	0.686972	5	6.94%
1.386294	4	1097	3.88	0.89081	7	9.72%
1.609438	5	1095	3.92	0.013857	4	5.56%
1.791759	6	1002	4.24		4	5.56%
Averages		1050	4.00		6	7.64%
StDev		48.16315	0.15		1.378405	1.91%
Practiced Performace:	Block 6 only			Homing Time		
Averages		1002	4.24	584.375	4	5.56%
StDev		272	0.44	106.1748		
Learning %		1.77%	6.28%			

Mouse with Forearm Support — user4

LN Block	Block#	Mean Mov	Ave. Thrup	Ttest time	Error	Error%
0	1	1433	3.01	0.799968	3	4.17%
0.693147	2	1480	2.97	0.458548	3	4.17%
1.098612	3	1464	2.97	0.079581	5	6.94%
1.386294	4	1346	3.25	0.659076	9	12.50%
1.609438	5	1357	3.14	0.095191	3	4.17%
1.791759	6	1240	3.64		4	5.56%
Averages		1387	3.16		5	6.25%
StDev		90.52747	0.26		2.345208	3.26%
Practiced Performace:	Block 6 only			Homing Time		
Averages		1240	3.64	595.6111	4	5.56%
StDev		402	0.46	82.54006		
Learning %		13.49%	21.00%			

Mouse user5

LN Block	Block#	Mean Mov	Ave. Thrup	Ttest time	Error	Error%
0	1	1157	3.71	0.138928	7	9.72%
0.693147	2	1071	3.65	0.45907	9	12.50%
1.098612	3	1054	3.84	0.888085	11	15.28%
1.386294	4	1012	3.92	0.882957	12	16.67%
1.609438	5	1057	2.76	0.015943	12	16.67%
1.791759	6	1134	3.57		9	12.50%
Averages		1081	3.58		10	13.89%
StDev		54.43325	0.42		2	2.78%
Practiced Performace:	Block 6 only			Homing Time		
Averages		1134	3.57	538.6111	9	12.50%
StDev		420	0.56	73.57636		
Learning %		2.02%	3.63%			

Command Chair

LN Block	Block#	Mean Mov	Ave. Thrup	Ttest time	Error	Error%
0	1	2130	2.12	0.98501	6	8.33%
0.693147	2	2119	2.17	0.169306	5	6.94%
1.098612	3	1931	2.20	0.647966	7	9.72%
1.386294	4	1883	2.36	0.749082	6	8.33%
1.609438	5	1840	2.33	0.521314	6	8.33%
1.791759	6	1861	2.36		7	9.72%
Averages		1961	2.26		6	8.56%
StDev		130.389	0.11		0.752773	1.05%
Practiced Performace:	Block 6 only			Homing Time		
Averages		1861	2.36	53.31944	7	9.72%
StDev		807	0.37	53.73955		
Learning %		12.65%	11.40%			

Mouse with Forearm Support

LN Block	Block#	Mean Mov	Ave. Thrup	Ttest time	Error	Error%
0	1	1339	3.23	0.009967	5	6.94%
0.693147	2	1213	3.28	0.171597	8	11.11%
1.098612	3	1141	3.84	0.062311	3	4.17%
1.386294	4	1058	3.98	0.39311	5	6.94%
1.609438	5	1076	3.78	0.043966	11	15.28%
1.791759	6	1209	3.76		4	5.56%
Averages		1173	3.65		6	8.33%
StDev		104.1733	0.31		2.966479	4.12%
Practiced Performace:	Block 6 only			Homing Time		
Averages		1209	3.76	646.3333	4	5.56%
StDev		386	0.53	112.1144		
Learning %		9.74%	16.33%			

Mouse user6

LN Block	Block#	Mean Mov	Ave. Thrup	Ttest time	Error	Error%
0	1	1057	3.81	0.099889	7	9.72%
0.693147	2	1000	4.41	9.51E-05	4	5.56%
1.098612	3	1209	3.69	0.452108	5	6.94%
1.386294	4	1156	4.06	0.097189	1	1.39%
1.609438	5	1086	4.19	0.701895	1	1.39%
1.791759	6	1074	4.15		2	2.78%
Averages		1097	4.05		3	4.63%
StDev		74.3767	0.26		2.42212	3.36%
Practiced Performace:	Block 6 only			Homing Time		
Averages		1074	4.15	569.0139	2	2.78%
StDev		317	0.47	110.0662		
Learning %		1.66%	8.93%			

Command Chair

LN Block	Block#	Mean Mov	Ave. Thrup	Ttest time	Error	Error%
0	1	2182	1.92	0.041927	7	9.72%
0.693147	2	2551	1.55	0.998404	11	15.28%
1.098612	3	2547	1.68	0.178309	3	4.17%
1.386294	4	2395	1.92	0.644594	2	2.78%
1.609438	5	2280	1.82	0.455826	9	12.50%
1.791759	6	2462	1.72		4	5.56%
Averages		2403	1.77		6	8.33%
StDev		148.3038	0.15		3.577709	4.97%
Practiced Performace:	Block 6 only			Homing Time		
Averages		2462	1.72	57.16667	4	5.56%
StDev		1104	0.21	49.23757		
Learning %		12.83%	10.28%			

Mouse with Forearm Support

LN Block	Block#	Mean Mov	Ave. Thrup	Ttest time	Error	Error%
0	1	1169	3.92	0.064902	1	1.39%
0.693147	2	1236	1.92	0.130379	6	8.33%
1.098612	3	1181	2.61	0.695819	4	5.56%
1.386294	4	1228	3.15	0.359858	2	2.78%
1.609438	5	1191	2.78	0.227581	2	2.78%
1.791759	6	1155	3.97		2	2.78%
Averages		1193	3.06		3	3.94%
StDev		32.54358	0.79		1.834848	2.55%
Practiced Performace:	Block 6 only			Homing Time		
Averages		1155	3.97	657.4167	2	2.78%
StDev		335	0.43	100.601		
Learning %		1.22%	1.26%			

Mouse user7

LN Block	Block#	Mean Mov	Ave. Thrup	Ttest time	Error	Error%
0	1	1522	3.03	0.925966	1	1.39%
0.693147	2	1528	3.04	0.122131	1	1.39%
1.098612	3	1641	2.83	0.142995	2	2.78%
1.386294	4	1515	2.91	0.562722	5	6.94%
1.609438	5	1483	3.03	0.206271	2	2.78%
1.791759	6	1547	2.73		4	5.56%
Averages		1539	2.93		3	3.47%
StDev		54.17212	0.13		1.643168	2.28%
Practiced Performace:	Block 6 only			Homing Time		
Averages		1547	2.73	542.9722	4	5.56%
StDev		507	0.33	86.64855		
Learning %		1.63%	10.02%			

Command Chair

LN Block	Block#	Mean Mov	Ave. Thrup	Ttest time	Error	Error%
0	1	2481	1.70	0.386585	5	6.94%
0.693147	2	2655	1.67	0.153577	4	5.56%
1.098612	3	2987	1.54	0.018325	3	4.17%
1.386294	4	2508	1.34	0.688389	8	11.11%
1.609438	5	2541	1.37	0.259535	3	4.17%
1.791759	6	2382	1.78		6	8.33%
Averages		2592	1.57		5	6.71%
StDev		212.5056	0.18		1.94079	2.70%
Practiced Performace:	Block 6 only			Homing Time		
Averages		2382	1.78	44.59722	6	8.33%
StDev		1220	0.35	51.60376		
Learning %		4.01%	4.81%			

Mouse with Forearm Support

LN Block	Block#	Mean Mov	Ave. Thrup	Ttest time	Error	Error%
0	1	4815	0.95	1.35E-13	1	1.39%
0.693147	2	1584	2.80	0.547718	2	2.78%
1.098612	3	1545	2.93	0.407758	2	2.78%
1.386294	4	1447	2.88	0.712516	8	11.11%
1.609438	5	1439	2.93	0.344514	6	8.33%
1.791759	6	1414	2.94		3	4.17%
Averages		2041	2.57		4	5.09%
StDev		1360.72	0.80		2.73252	3.80%
Practiced Performace:	Block 6 only			Homing Time		
Averages		1414	2.94	556.2778	3	4.17%
StDev		473	0.33	100.4699		
Learning %		70.64%	209.99%			

Mouse user8

LN Block	Block#	Mean Mov	Ave. Thrup	Ttest time	Error	Error%
0	1	6903	0.68	8.5E-28	0	0.00%
0.693147	2	1575	2.90	0.406799	5	6.94%
1.098612	3	1630	2.97	0.063039	1	1.39%
1.386294	4	1488	3.20	0.998726	2	2.78%
1.609438	5	1488	3.17	0.739178	2	2.78%
1.791759	6	1531	3.03		4	5.56%
Averages		2436	2.66		2	3.24%
StDev		2189.213	0.98		1.861899	2.59%
Practiced Performace:	Block 6 only			Homing Time		
Averages		1531	3.03	534.1528	4	5.56%
StDev		539	0.30	78.87084		
Learning %		77.82%	345.49%			

Command Chair

LN Block	Block#	Mean Mov	Ave. Thrup	Ttest time	Error	Error%
0	1	3093	1.28	0.490527	8	11.11%
0.693147	2	2956	1.48	0.951654	4	5.56%
1.098612	3	3017	1.49	0.799709	6	8.33%
1.386294	4	2996	1.17	0.930706	4	5.56%
1.609438	5	2917	1.47	0.024736	5	6.94%
1.791759	6	2494	1.78		2	2.78%
Averages		2912	1.44		5	6.71%
StDev		213.4765	0.21		2.041241	2.84%
Practiced Performace:	Block 6 only			Homing Time		
Averages		2494	1.78	58.93056	2	2.78%
StDev		767	0.31	75.32826		
Learning %		19.37%	38.72%			

Mouse with Forearm Support

LN Block	Block#	Mean Mov	Ave. Thrup	Ttest time	Error	Error%
0	1	2080	2.57	8.56E-10	2	2.78%
0.693147	2	1587	2.92	0.665913	1	1.39%
1.098612	3	1556	2.94	0.039332	2	2.78%
1.386294	4	1760	2.94	0.010529	2	2.78%
1.609438	5	1586	3.05	0.7823	0	0.00%
1.791759	6	1574	2.93		2	2.78%
Averages		1691	2.89		2	2.08%
StDev		204.994	0.16		0.83666	1.16%
Practiced Performace:	Block 6 only			Homing Time		
Averages		1574	2.93	649.875	2	2.78%
StDev		493	0.48	184.4446		
Learning %		24.34%	13.98%			

Mouse		user9				
LN Block	Block#	Mean Move	Ave. Thrup	Ttest time	Error	Error%
0	1	2466	1.93	0.000314	2	2.78%
0.693147	2	1943	2.47	0.235642	0	0.00%
1.098612	3	1829	2.41	0.728104	1	1.39%
1.386294	4	1775	2.49	4.16E-05	2	2.78%
1.609438	5	2356	1.84	4.99E-08	4	5.56%
1.791759	6	1722	2.61		1	1.39%
Averages		2015	2.29		2	2.31%
StDev		317.1096	0.32		1.36626	1.90%
Practiced Performace:	Block 6 only			Homing Time		
Averages		1722	2.61	588.8472	1	1.39%
StDev		579	0.22	91.706		
Learning %		30.16%	35.30%			

Mouse		user10				
LN Block	Block#	Mean Move	Ave. Thrup	Ttest time	Error	Error%
0	1	5337	0.89	2.4E-25	2	2.78%
0.693147	2	1424	3.45	0.986722	5	6.94%
1.098612	3	1432	3.49	0.19478	1	1.39%
1.386294	4	1321	3.82	0.036735	1	1.39%
1.609438	5	1455	3.58	0.337392	1	1.39%
1.791759	6	1537	3.40		1	1.39%
Averages		2084	3.10		2	2.55%
StDev		1594.866	1.09		1.602082	2.23%
Practiced Performace:	Block 6 only			Homing Time		
Averages		1537	3.40	595.5278	1	1.39%
StDev		544	0.50	67.38098		
Learning %		71.21%	281.54%			

Command Chair						
LN Block	Block#	Mean Move	Ave. Thrup	Ttest time	Error	Error%
0	1	2649	1.41	0.644412	17	23.61%
0.693147	2	2898	1.41	0.194385	10	13.89%
1.098612	3	2743	1.49	0.141202	7	9.72%
1.386294	4	2518	1.66	0.23408	9	12.50%
1.609438	5	2356	1.84	0.641972	4	5.56%
1.791759	6	2280	1.79		7	9.72%
Averages		2574	1.60		9	12.50%
StDev		235.2202	0.19		4.427189	6.15%
Practiced Performace:	Block 6 only			Homing Time		
Averages		2280	1.79	33.22222	7	9.72%
StDev		1006	0.26	39.3762		
Learning %		13.93%	27.19%			

Command Chair						
LN Block	Block#	Mean Move	Ave. Thrup	Ttest time	Error	Error%
0	1	11106	0.41	0.151298	6	8.33%
0.693147	2	10359	0.47	2.86E-18	3	4.17%
1.098612	3	2422	1.45	0.19515	2	2.78%
1.386294	4	2280	2.14	0.953772	0	0.00%
1.609438	5	2284	2.12	0.438533	1	1.39%
1.791759	6	2346	2.03		1	1.39%
Averages		5133	1.44		2	3.01%
StDev		4344.426	0.81		2.136976	2.97%
Practiced Performace:	Block 6 only			Homing Time		
Averages		2346	2.03	30.23611	1	1.39%
StDev		967	0.33	43.96621		
Learning %		78.87%	400.48%			

Mouse with Forearm Support						
LN Block	Block#	Mean Move	Ave. Thrup	Ttest time	Error	Error%
0	1	3032	1.46	7.57E-05	4	5.56%
0.693147	2	1740	2.45	0.971101	2	2.78%
1.098612	3	1800	2.58	0.378878	3	4.17%
1.386294	4	1697	2.60	0.292568	2	2.78%
1.609438	5	1826	2.41	0.503016	3	4.17%
1.791759	6	1755	2.53		3	4.17%
Averages		1975	2.34		3	3.94%
StDev		519.8224	0.44		0.752773	1.05%
Practiced Performace:	Block 6 only			Homing Time		
Averages		1755	2.53	661.125	3	4.17%
StDev		677	0.39	144.2889		
Learning %		42.11%	73.70%			

Mouse with Forearm Support						
LN Block	Block#	Mean Move	Ave. Thrup	Ttest time	Error	Error%
0	1	3742	1.40	4.56E-10	6	8.33%
0.693147	2	1347	3.67	0.073551	2	2.78%
1.098612	3	1502	3.56	0.252267	0	0.00%
1.386294	4	1373	2.50	0.008418	2	2.78%
1.609438	5	1600	3.47	0.012164	2	2.78%
1.791759	6	1374	3.67		0	0.00%
Averages		1823	3.04		2	2.78%
StDev		944.9084	0.92		2.19089	3.04%
Practiced Performace:	Block 6 only			Homing Time		
Averages		1374	3.67	570.8194	0	0.00%
StDev		599	0.62	215.0749		
Learning %		63.28%	162.76%			

Mouse user11

LN Block	Block#	Mean Mov	Ave. Thrup	Ttest time	Error	Error%
0	1	1341	3.34	0.093056	2	2.78%
0.693147	2	1261	3.49	0.325767	3	4.17%
1.098612	3	1318	3.38	0.15153	2	2.78%
1.386294	4	1254	3.54	0.541652	1	1.39%
1.609438	5	1289	3.50	0.040222	3	4.17%
1.791759	6	1186	3.88		1	1.39%
Averages		1275	3.52		2	2.78%
StDev		54.57193	0.19		0.894427	1.24%
Practiced Performace:	Block 6 only			Homing Time		
Averages		1186	3.88	684.3611	1	1.39%
StDev		398	0.41	124.2018		
Learning %		11.55%	16.10%			

Command Chair

LN Block	Block#	Mean Mov	Ave. Thrup	Ttest time	Error	Error%
0	1	5789	0.71	4.81E-10	7	9.72%
0.693147	2	1967	2.10	0.289903	5	6.94%
1.098612	3	2087	2.06	0.282729	2	2.78%
1.386294	4	2157	1.95	0.002188	5	6.94%
1.609438	5	1830	2.40	0.70845	0	0.00%
1.791759	6	1844	2.37		2	2.78%
Averages		2612	1.93		4	4.86%
StDev		1561.709	0.63		2.588436	3.60%
Practiced Performace:	Block 6 only			Homing Time		
Averages		1844	2.37	50.77778	2	2.78%
StDev		599	0.28	47.99126		
Learning %		68.14%	235.00%			

Mouse with Forearm Support

LN Block	Block#	Mean Mov	Ave. Thrup	Ttest time	Error	Error%
0	1	1764	2.61	0.007476	1	1.39%
0.693147	2	1295	3.41	0.131937	2	2.78%
1.098612	3	1236	3.58	0.039286	3	4.17%
1.386294	4	1142	3.95	0.204975	0	0.00%
1.609438	5	1177	3.66	0.034255	3	4.17%
1.791759	6	1285	3.49		2	2.78%
Averages		1316	3.45		2	2.55%
StDev		227.2251	0.45		1.169045	1.62%
Practiced Performace:	Block 6 only			Homing Time		
Averages		1285	3.49	783.8056	2	2.78%
StDev		385	0.41	112.1868		
Learning %		27.16%	33.44%			

Mouse user12

LN Block	Block#	Mean Mov	Ave. Thrup	Ttest time	Error	Error%
0	1	3459	1.34	2.72E-09	1	1.39%
0.693147	2	1348	3.42	0.244963	4	5.56%
1.098612	3	1400	3.31	0.576157	3	4.17%
1.386294	4	1435	3.35	0.026145	4	5.56%
1.609438	5	1332	3.43	0.833954	3	4.17%
1.791759	6	1336	3.48		1	1.39%
Averages		1718	3.06		3	3.70%
StDev		853.9467	0.84		1.36626	1.90%
Practiced Performace:	Block 6 only			Homing Time		
Averages		1336	3.48	616.8889	1	1.39%
StDev		290	0.35	69.36849		
Learning %		61.39%	159.53%			

Command Chair

LN Block	Block#	Mean Mov	Ave. Thrup	Ttest time	Error	Error%
0	1	2567	1.40	0.313821	12	16.67%
0.693147	2	2378	1.68	0.095176	11	15.28%
1.098612	3	2177	1.72	0.758746	14	19.44%
1.386294	4	2159	1.70	0.281251	19	26.39%
1.609438	5	2397	1.73	0.139961	9	12.50%
1.791759	6	2150	1.81		14	19.44%
Averages		2305	1.67		13	18.29%
StDev		170.0201	0.14		3.430258	4.76%
Practiced Performace:	Block 6 only			Homing Time		
Averages		2150	1.81	58.86111	14	19.44%
StDev		879	0.26	61.85884		
Learning %		16.26%	29.71%			

Mouse with Forearm Support

LN Block	Block#	Mean Mov	Ave. Thrup	Ttest time	Error	Error%
0	1	1682	2.74	0.002793	5	6.94%
0.693147	2	1506	3.15	0.779892	5	6.94%
1.098612	3	1506	3.20	0.000563	6	8.33%
1.386294	4	1718	3.01	0.004745	1	1.39%
1.609438	5	1530	3.26	0.002959	0	0.00%
1.791759	6	1371	3.50		1	1.39%
Averages		1552	3.14		3	4.17%
StDev		127.9957	0.26		2.607681	3.62%
Practiced Performace:	Block 6 only			Homing Time		
Averages		1371	3.50	615.3194	1	1.39%
StDev		343	0.37	157.2197		
Learning %		18.50%	28.10%			

B.7 Raw Workstation Throughput Data

Overall

Average Chair Time

user	Pointing Ti	Homing Tir	Typing Tim	First Totals	Mouse Hor	Finish Time	Totals	Pointing Er	Typing Errc	Total Error(0/1/2)	
1	1641.69	663.6897	1181.621	3487	94.93103	1646.207	3581.931	0.1	0.42	0.52	StDev
2	2371.528	1341.389	3597.722	7310.639	208.8611	2790.944	7519.5	0.04	0.26	0.3	
3	2101.114	734.1714	1555.429	4390.714	119.0857	2397.057	4509.8	0.1	0.22	0.32	
4	2927.697	1447.091	4443.697	8818.485	98.30303	2741.879	8916.788	0.12	0.28	0.4	
5	2073.129	954.0645	2671.226	5698.419	163.3548	2448.839	5861.774	0.22	0.22	0.44	
6	2239.533	1128.267	2316.333	5684.133	114.2	3176.9	5798.333	0.12	0.32	0.44	
7	2033.042	805.7083	2400.542	5239.292	126	2458	5365.292	0.16	0.48	0.64	
8	2331.021	1289.277	3892.043	7512.34	125.0426	2896.723	7637.383	0	0.06	0.06	
9	2558.091	1130.318	2528.091	6216.5	131.1364	3699.045	6347.636	0.22	0.42	0.64	
10	2235.133	1290.8	2725.933	6251.867	195.3333	5256.2	6447.2	0.08	0.36	0.44	
11	2458.875	1410.417	3806.208	7675.5	133.2917	2913.292	7808.792	0.04	0.48	0.52	
12	1867.6	668.9667	1026.767	3563.333	77.1	2446.933	3640.433	0.22	0.26	0.48	
Average	2236.538	1072.013	2678.801	5987.352	132.22	2906.002	6119.572	0.118333	0.315	0.433333	
StDev	334.9496	295.0409	1094.15	1664.501	39.30687	890.9956	1679.191	0.074569	0.123913	0.157788	

Average Fixed Support Time

user	Pointing Ti	Homing Tir	Typing Tim	First Totals	Mouse Hor	Finish Time	Totals	Pointing Er	Typing Errc	Total Error(0/1/2)	
1	1206.371	1015.686	990.2571	3212.314	564.5429	702.7143	3776.857	0.1	0.26	0.36	StDev
2	1374.224	1319.224	1778.122	4471.571	823.5306	994.551	5295.102	0	0.02	0.02	
3	1187.792	608.375	679.9583	2476.125	418.625	783.2708	2894.75	0	0.04	0.04	
4	1434.154	1080	1707.821	4221.974	543.0769	957.5641	4765.051	0.04	0.18	0.22	
5	1352.261	955	1787.696	4094.957	641.2174	710.3696	4736.174	0.02	0.06	0.08	
6	1267.979	854.0417	1017.625	3139.646	597.0208	820.9167	3736.667	0.02	0.02	0.04	
7	1253.76	1164.08	1350	3767.84	684.16	892.44	4452	0.06	0.5	0.56	
8	1505.727	1084.182	1762.955	4352.864	808.5227	900.2955	5161.386	0	0.12	0.12	
9	1439.69	939.7381	1647.286	4026.714	562.2857	1094.119	4589	0.08	0.08	0.16	
10	1239.1	950.65	970.1	3159.85	667.175	863.95	3827.025	0.02	0.18	0.2	
11	1325.886	1268.6	1179.486	3773.971	925.0571	808.6	4699.029	0.04	0.3	0.34	
12	1274.341	913.9024	988.3171	3176.561	619.9024	798.1951	3796.463	0.02	0.16	0.18	
Average	1321.774	1012.79	1321.635	3656.199	654.5931	860.5822	5171.374	0.033333	0.16	0.193333	
StDev	100.8795	191.3875	398.3163	614.9094	140.0847	115.2573	767.3153	0.032287	0.140648	0.159848	

Average Mouse Time

user	Pointing Ti	Homing Tir	Typing Tim	First Totals	Mouse Hor	Finish Time	Totals	Pointing Er	Typing Errc	Total Error(0/1/2)	
1	1190.806	868.4444	891.0556	2950.306	467.8333	804.25	3418.139	0.12	0.2	0.32	StDev
2	1447.422	1207.711	1176.156	3831.289	724.1778	898.8222	4555.467	0	0.1	0.1	
3	1192.213	587.2766	690.2766	2469.766	499.8936	700.0851	2969.66	0.04	0.02	0.06	
4	1489.692	1128.282	1702.923	4320.897	564.4872	1574.205	4885.385	0.04	0.18	0.22	
5	1182.262	854.119	1363.19	3399.571	547.6905	649.5714	3947.262	0.14	0.02	0.16	
6	1308.896	862.2292	1174.854	3345.979	618.6667	793.2292	3964.646	0	0.04	0.04	
7	1403.208	1052.375	1699.5	4155.083	654.7917	959.7083	4809.875	0.06	0.5	0.56	
8	1313.17	1030.191	1589.277	3932.638	638.5532	855.9787	4571.191	0.02	0.04	0.06	
9	1598.605	908.3947	2020.368	4527.368	606.1579	986.6053	5133.526	0.02	0.22	0.24	
10	1369.686	991.0857	1286.8	3647.571	712.6857	871.8286	4360.257	0.08	0.22	0.3	
11	1379.45	1214.3	993.4	3587.15	895.775	861.275	4482.925	0	0.2	0.2	
12	1198.707	909.6829	730.3171	2838.707	577.9512	854.122	3416.659	0.06	0.14	0.2	
Average	1339.51	967.841	1276.51	3583.861	625.722	900.8067	5110.389	0.048333	0.156667	0.205	
StDev	134.1255	176.1473	416.7672	620.4884	114.6177	232.6129	826.7957	0.046286	0.134254	0.145258	

Average Chair StDev

user	Pointing Ti	Homing Tir	Typing Tim	First Totals	Mouse Hor	Finish Time	Totals	Pointing Er	Typing Erro	Total Error(0/1/2)
1	411.601	227.9645	308.0799	548.1567	159.5124	544.1388	778.8923	0.303046	0.498569	0.67733
2	2186.267	202.6732	759.3347	2273.061	230.7593	975.1958	2373.826	0.197949	0.443087	0.505076
3	1549.56	326.8119	547.9194	1891.265	156.9469	1007.101	2357.672	0.303046	0.418452	0.512696
4	1802.28	370.4772	1036.958	2343.508	123.6286	643.134	2422.462	0.328261	0.453557	0.606092
5	922.9806	241.7232	662.347	1137.591	211.1804	450.0546	1210.554	0.418452	0.418452	0.611455
6	859.2686	306.3184	827.2956	1310.375	151.0671	1110.821	1849.848	0.328261	0.471212	0.577115
7	548.3562	522.783	1028.847	1524.641	130.6938	454.3298	1669.74	0.370328	0.504672	0.69282
8	1070.696	307.0637	1694.883	1978.313	305.5051	618.5884	2028.164	0	0.239898	0.239898
9	1376.689	258.9067	727.319	1282.155	134.7337	875.502	1167.736	0.418452	0.498569	0.631163
10	812.5656	489.8739	1148.764	1478.011	302.1511	7070.866	7849.573	0.274048	0.484873	0.577115
11	699.9119	332.0013	1450.158	1547.708	138.1475	1070.818	2025.951	0.197949	0.504672	0.504672
12	640.793	253.6169	244.595	813.4896	126.0611	757.8478	1259.312	0.418452	0.443087	0.646498
Average	1073.414	320.0178	869.7084	1510.689	180.8656	1298.2	2249.477	0.29652	0.448259	0.565161
(Std Error).										

Average Fixed Support StDev

user	Pointing Ti	Homing Tir	Typing Tim	First Totals	Mouse Hor	Finish Time	Totals	Pointing Er	Typing Erro	Total Error(0/1/2)
1	164.9724	254.9328	361.2479	483.8666	59.71173	171.8076	554.571	0.303046	0.443087	0.597956
2	252.8757	220.8542	599.1374	815.0356	160.3286	288.8631	923.1954	0	0.141421	0.141421
3	138.4966	99.15143	300.895	379.885	123.5601	226.8201	529.3945	0	0.197949	0.197949
4	201.8447	336.3178	495.7454	791.3629	76.29251	226.7654	904.8804	0.197949	0.388088	0.418452
5	401.6819	357.6958	390.1561	794.7709	121.8161	155.6282	950.6495	0.141421	0.239898	0.274048
6	203.724	224.3883	370.3982	573.4505	126.9331	310.7928	752.7893	0.141421	0.141421	0.197949
7	201.3406	252.9628	416.3808	596.7931	124.5544	233.1232	636.6374	0.239898	0.505076	0.611455
8	348.871	140.6616	565.699	860.1123	145.8291	198.9126	1039.546	0	0.328261	0.328261
9	295.5725	261.733	553.7888	743.0385	73.00461	437.2721	868.6731	0.274048	0.274048	0.370328
10	146.6683	378.6807	356.2477	714.5964	85.35263	281.9423	785.8153	0.141421	0.388088	0.404061
11	173.9051	413.5633	710.598	962.6684	234.7287	189.7404	1036.735	0.197949	0.46291	0.557326
12	228.9019	95.4075	349.989	561.7107	124.6495	198.7212	676.7438	0.141421	0.370328	0.388088
Average	229.9045	253.0291	455.8569	689.7742	121.3968	243.3658	804.9692	0.148214	0.323381	0.373941
(Std Error).										

Average Mouse StDev

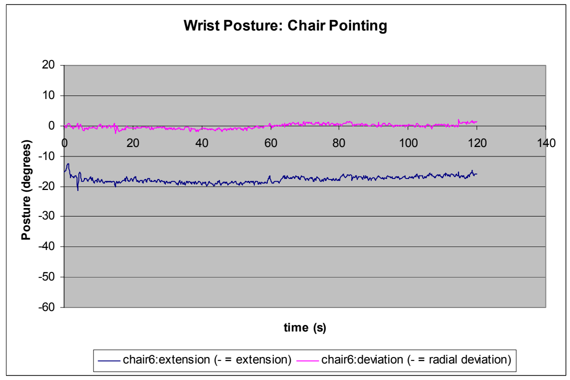
user	Pointing Ti	Homing Tir	Typing Tim	First Totals	Mouse Hor	Finish Time	Totals	Pointing Er	Typing Erro	Total Error(0/1/2)
1	117.2521	223.5258	311.6095	374.0859	111.7769	206.2529	446.7492	0.328261	0.404061	0.551066
2	763.0893	172.3784	209.9371	824.8718	103.9874	222.9432	892.7764	0	0.303046	0.303046
3	162.4105	163.3706	314.5028	491.3309	121.2038	225.0135	655.9202	0.197949	0.141421	0.239898
4	316.9872	251.0923	516.7194	733.2305	72.51674	3494.83	3429.212	0.197949	0.388088	0.418452
5	128.4159	171.8921	394.5878	421.4675	64.41273	137.0151	469.7952	0.35051	0.141421	0.370328
6	210.8984	157.9859	542.2281	743.4873	166.8026	369.0351	967.6999	0	0.197949	0.197949
7	219.4196	192.5512	592.5567	625.2932	157.9708	294.7328	700.4512	0.239898	0.505076	0.577115
8	243.6869	195.9055	271.2568	469.9178	58.33666	147.8622	517.503	0.141421	0.197949	0.239898
9	469.9379	209.8671	632.187	908.7628	106.0486	245.2202	1011.293	0.141421	0.418452	0.431419
10	363.2371	214.1352	541.3916	621.4658	109.7864	229.6562	685.4451	0.274048	0.418452	0.46291
11	246.3046	243.6349	403.2354	732.0491	186.9608	195.2834	863.4108	0	0.404061	0.404061
12	211.073	155.1713	163.1341	368.0513	55.79962	455.2494	627.6641	0.239898	0.35051	0.451754
Average	287.726	195.9592	407.7789	609.5012	109.6336	518.5912	938.9933	0.175946	0.32254	0.387325
(Std Error).										

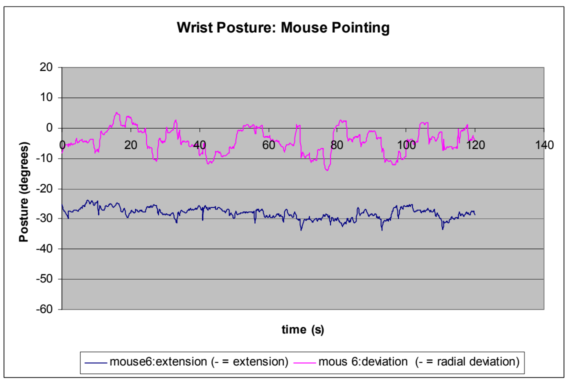
B.8 Compiled Questionnaire Data

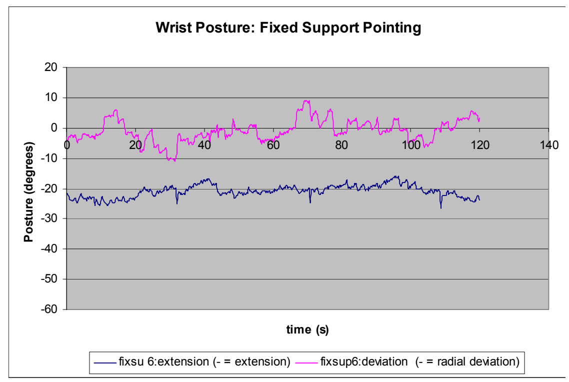
			user 1	user 2	user 3	user 4	user 5	user 6	user 7	user 8	user 9	user 10	user 11	user 12
Learning	out of 12	**Did you find this device easy to learn? Explain.**												
		8 Easy/Predictable learning curve	1		1	1			1	1		1	1	1
		2 Easy but precision is difficult		1			1							
		1 Easy but keyboard is not sensitive enough									1			
		1 No						1						
total														
	out of 12	**How would you compare learning the Comand Chair to learning a regular mouse?**												
		0 Easier												
		4 Similar		1						1	1	1		
		7 Harder	1		1	1	1	1					1	1
		1 Unsure							1					
	out of 15	**What did find hardest to learn about the Command Chair?**												
		4 Precision/Smoothness of pointer	1	1				1					1	
		3 Limited range of pointer			1		1			1				
		4 Split keyboard				1		1			1	1		
		2 Soft keyboard				1			1					
		1 Mouse buttons causes change in default typing position						1						
		1 Trouble keeping the mouse steady while typing												1
Practiced Skill	out of 14	**At the end of the study, did you feel like you could control the Command Chair in all situations? If not, where did you have**												
		6 Precision of pointer	1	1		1		1		1		1		
		1 Typing	1											
		2 Stability of pointer while typing			1									1
		1 Limited range of pointer					1							
		1 Speed						1						
		2 For the most part							1				1	
		1 Yes									1			
	out of 12	**Did you find the Command Chair comfortable to use? If not, why not?**												
		7 Yes	1		1	1			1	1		1	1	
		1 Okay					1							
		4 No		1				1			1			1
	out of 13	**Did you have any fatigue from using the Command Chair? If so, where?**												
		7 No	1		1	1	1		1	1	1			
		2 Outside of hand/wrist		1									1	
		2 Slightly in upper arm/shoulder						1				1		
		1 Forearm											1	
		1 Back												1
Overall	out of 12	**If you could use the Command Chair with your computer, would you? Explain.**												
		5 Positive answers		1	1						1	1		1
		7 Negative answers	1			1	1	1	1	1			1	
	ouf of 15	**Would you prefer to use it for certain tasks? Examples: word preocessing, spreadsheets, video games.**												
		2 Word processing				1							1	
		5 Spreadsheets		1	1							1	1	1
		6 Video games	1		1	1	1		1	1				
		2 No						1			1			
	out of 12	**Would you like to be able to switch between the hand mouse and the Command Chair?**												
		3 Yes	1				1			1				
		7 No		1	1	1		1			1	1	1	
		2 Maybe							1					1
	out of 12	**Can you imagine any circumstances in which someone might prefer the Command Chair to a conventional mouse?**												
		1 Yes, for repetitive stress sufferers	1											
		9 Yes, for certain applications		1	1	1		1		1	1	1	1	1
		1 Yes, for touch typists					1							

	Average		user 1	user 2	user 3	user 4	user 5	user 6	user 7	user 8	user 9	user 10	user 11	user 12
Effort		**Mouse Effort**												
	7	Fingers/Wrist		7										
	3.25	Arm	5	4	8	1	7	0.5	2	1	3	2	0.5	5
	1.1666667	Shoulder	0	0	1	1	2	1	2	2	1	0	1	3
	1.5416667	Neck	0	0	4	4	2	1	2	3	0	0	0.5	2
		Command Chair Effort												
	1	Fingers/Wrist		1										
	2.625	Arm	2	6	2	1	3	4	4	2	0.5	1	2	4
	3.2083333	Shoulder	2	1	5	2	8	4	4	3	3	0.5	1	5
	1.0416667	Neck	0	0	2	1	2	0	4	1	0	0	0.5	2
Quantitative Device Assessment		**The force required for actuation was:**												
	0.7604167	Supported mouse	0.13	1.25	0.38	0.63	2.50	0.63	1.25	0.00	0.88	0.38	0.13	1.00
	0.84375	Unsupported mouse	0.13	2.13	0.38	0.63	2.50	1.63	1.25	0.00	0.00	0.38	0.13	1.00
	1.8229167	Chair	0.25	1.75	1.63	0.63	3.75	3.75	3.13	2.50	2.25	0.38	0.13	1.75
		Smoothness during operation was:												
	0.7708333	S	0.13	0.25	2.25	0.50	1.25	0.50	0.63	0.00	1.13	1.13	0.25	1.25
	1.03125	U	1.13	1.25	2.25	0.50	1.25	1.25	0.63	2.38	0.13	0.13	0.25	1.25
	3.5625	C	3.50	3.25	3.75	3.63	3.75	4.88	3.00	3.75	5.00	3.13	1.50	3.63
		The mental effort required for use was:												
	0.78125	S	0.25	1.38	2.25	0.38	0.13	1.25	0.50	1.25	0.00	0.50	0.50	1.00
	0.71875	U	0.25	1.38	2.25	0.38	0.13	0.38	0.50	1.25	0.13	0.50	0.50	1.00
	2.0833333	C	1.13	1.38	2.50	1.25	2.50	4.88	2.00	3.75	2.38	1.13	0.50	1.63
		The physical effort required for use was:												
	0.84375	S	0.25	1.13	1.38	0.38	1.25	0.63	0.38	1.13	0.00	0.50	0.50	2.63
	1.2291667	U	2.38	2.38	1.38	0.38	2.50	0.63	0.38	1.13	0.00	0.50	0.50	2.63
	1.5520833	C	0.25	1.13	0.63	1.13	3.75	2.50	1.75	2.50	0.00	0.63	0.88	3.50
		Accurate pointing was:												
	0.4895833	S	0.13	0.63	0.75	0.38	0.13	0.38	0.38	0.00	0.00	1.25	0.63	1.25
	0.8541667	U	1.13	1.63	0.75	0.38	1.25	1.50	0.50	1.13	0.00	0.13	0.63	1.25
	2.9375	C	2.38	2.50	3.63	4.88	2.50	4.88	1.50	3.75	2.38	2.50	1.50	2.88
		Operation speed was:												
	1.6770833	S	0.25	1.25	0.50	0.38	1.25	2.50	2.50	1.25	2.63	2.50	2.63	2.50
	1.9479167	U	0.25	2.50	0.50	0.38	2.50	2.00	2.50	2.50	2.63	2.50	2.63	2.50
	3.1458333	C	1.25	1.25	3.50	3.75	3.75	4.75	4.75	3.75	3.75	2.50	1.25	3.50
		Finger fatigue:												
	1.4791667	S	1.13	2.00	4.88	1.13	2.50	0.50	0.25	2.50	0.13	0.50	0.13	2.13
	1.6770833	U	1.13	3.50	4.50	1.13	3.75	0.50	0.25	2.50	0.13	0.50	0.13	2.13
	1.2708333	C	1.13	0.63	0.75	1.13	3.75	2.00	0.38	1.13	0.13	0.50	0.13	3.63
		Wrist fatigue:												
	1.6666667	S	1.25	1.63	4.75	0.38	1.25	0.63	0.38	1.38	1.25	3.13	0.50	3.50
	2.5	U	3.38	3.88	4.50	1.25	3.75	1.63	0.38	2.50	2.38	2.38	0.50	3.50
	0.4895833	C	0.25	1.63	0.25	0.38	1.25	0.13	0.50	0.00	0.00	0.50	0.50	0.50
		Arm fatigue:												
	1.3333333	S	0.25	1.38	4.00	0.38	2.50	0.25	0.50	1.25	1.25	2.38	0.38	1.50
	1.7916667	U	2.38	2.75	3.63	0.38	4.88	0.88	0.50	1.25	1.13	1.75	0.38	1.63
	1.3229167	C	1.13	1.38	0.38	0.38	2.50	2.50	0.63	1.25	0.00	1.25	1.13	3.38
		Shoulder fatigue:												
	0.8333333	S	0.13	0.75	1.25	0.38	1.25	1.13	0.63	0.13	0.50	0.25	1.38	2.25
	1.15625	U	0.13	1.13	0.88	0.38	3.75	0.25	0.63	2.50	0.38	0.25	1.38	2.25
	2.0208333	C	0.13	1.88	2.88	0.38	4.88	2.00	3.25	2.50	1.13	0.75	1.38	3.13
		Neck fatigue:												
	0.71875	S	0.13	0.25	3.63	0.38	1.38	0.38	0.50	0.00	0.00	0.13	0.88	1.00
	1.0833333	U	0.13	0.25	3.63	1.25	4.88	0.38	0.50	0.00	0.00	0.13	0.88	1.00
	0.6041667	C	0.13	0.25	1.13	0.38	2.50	0.38	0.63	0.00	0.00	0.13	0.75	1.00
		General comfort:												
	1.2708333	S	0.13	0.88	3.63	0.38	0.13	0.25	2.63	0.00	2.50	1.25	1.00	2.50
	1.9270833	U	3.50	2.88	3.38	1.25	2.50	1.75	0.50	2.50	1.13	0.38	0.88	2.50
	1.3541667	C	0.13	1.13	0.88	0.38	3.75	1.13	2.13	0.00	1.25	1.25	1.75	2.50

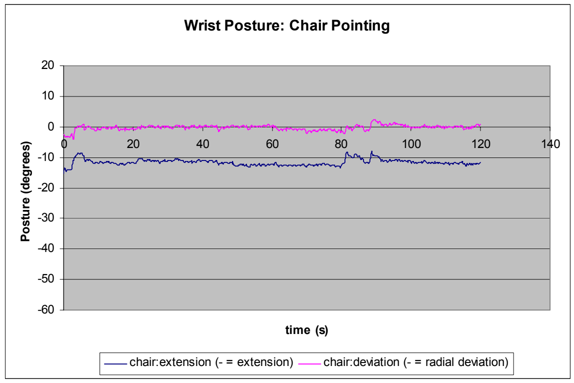
B.9 User Wrist Posture Graphs

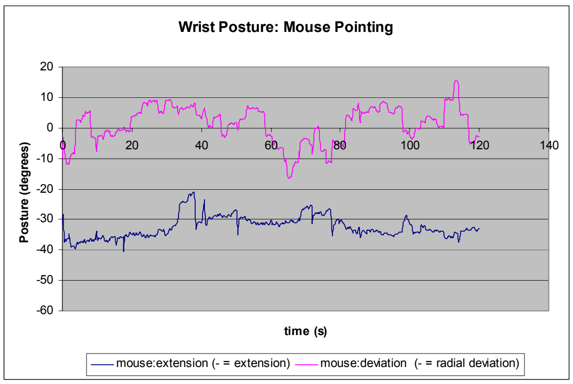


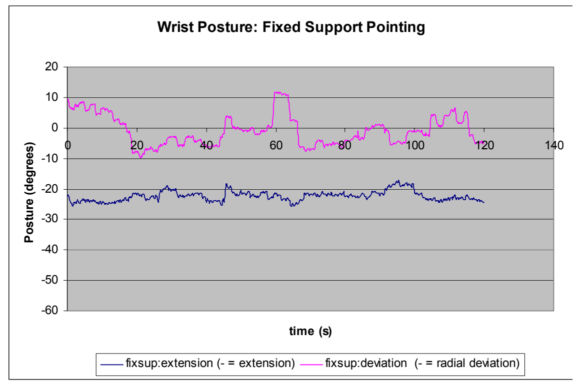




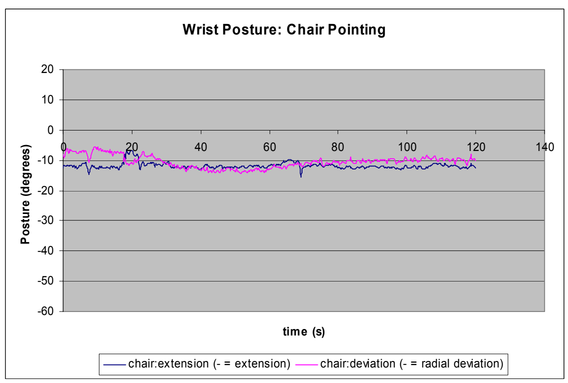
User 1 Wrist Posture Graphs – Pointing Block 6

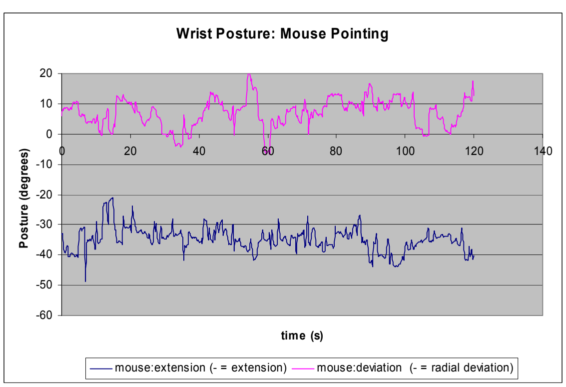


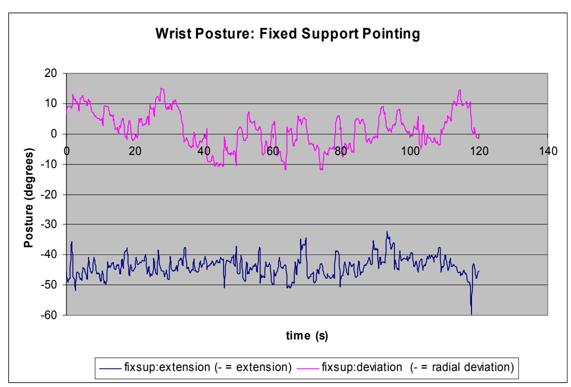




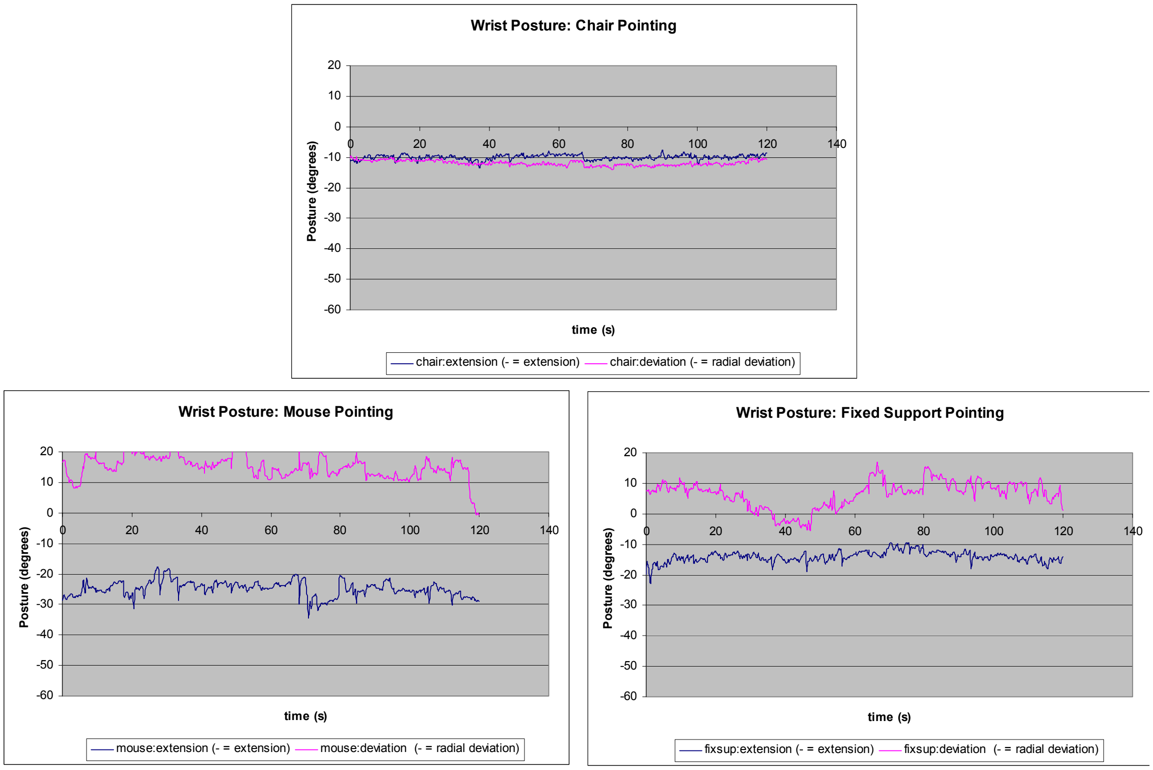
User 2 Wrist Posture Graphs – Pointing Block 6



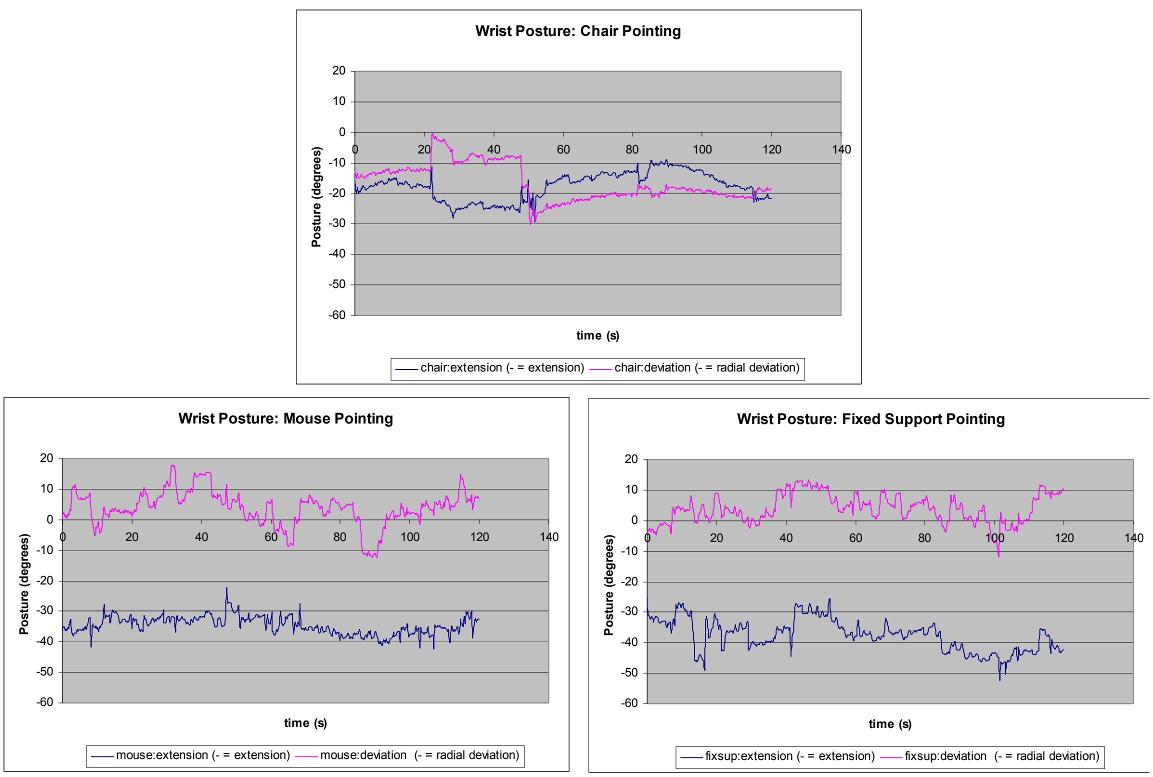




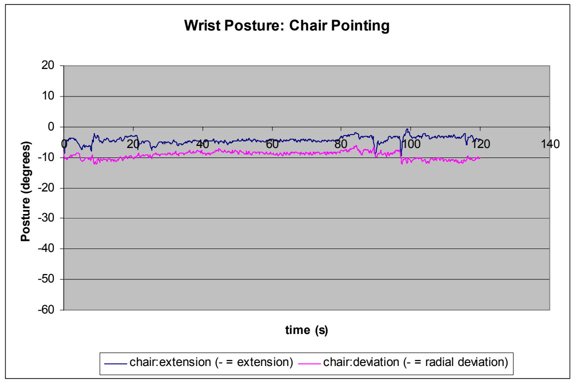
User 3 Wrist Posture Graphs – Pointing Block 6

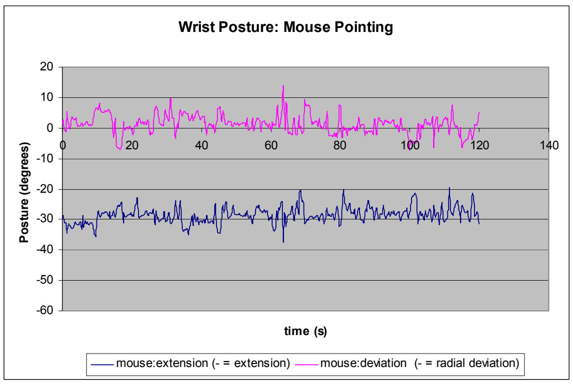


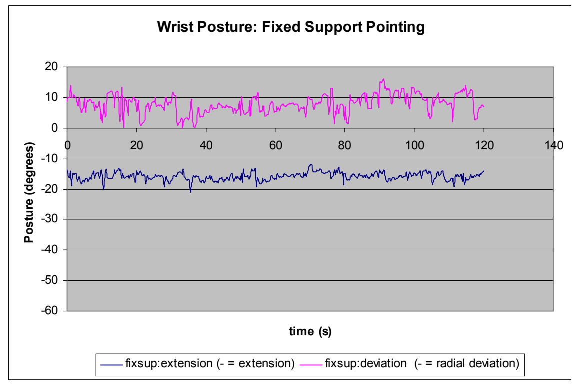
User 4 Wrist Posture Graphs – Pointing Block 6



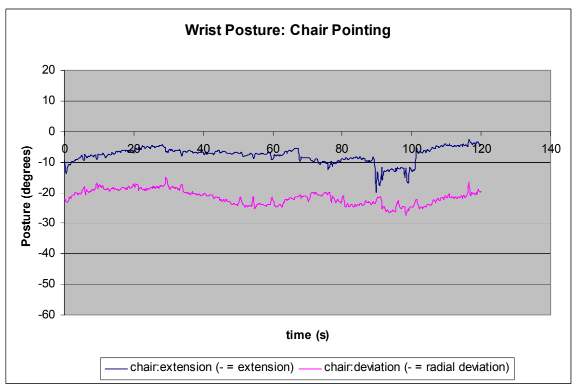
User 5 Wrist Posture Graphs – Pointing Block 6

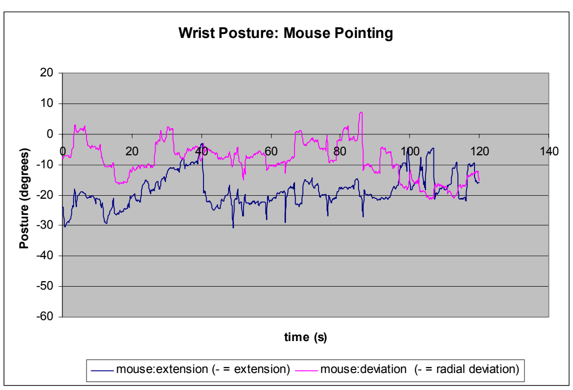


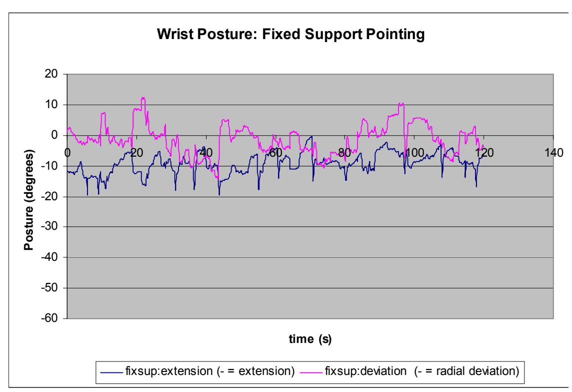




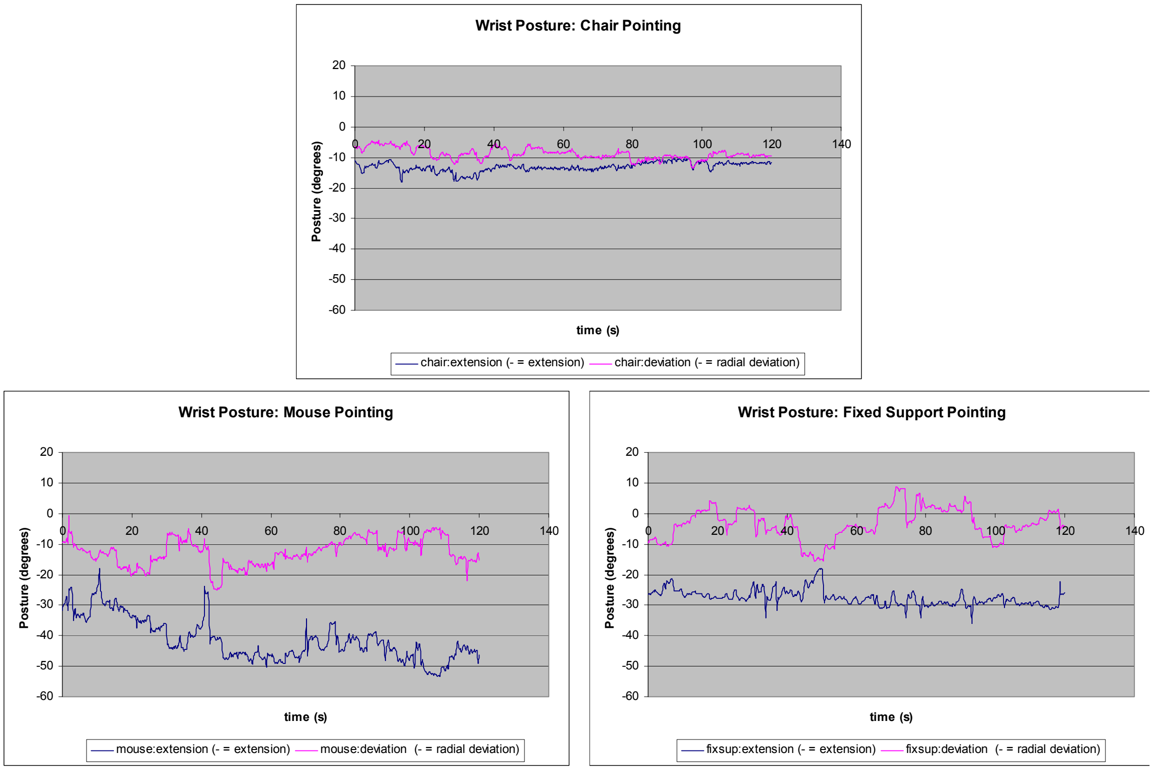
User 6 Wrist Posture Graphs – Pointing Block 6



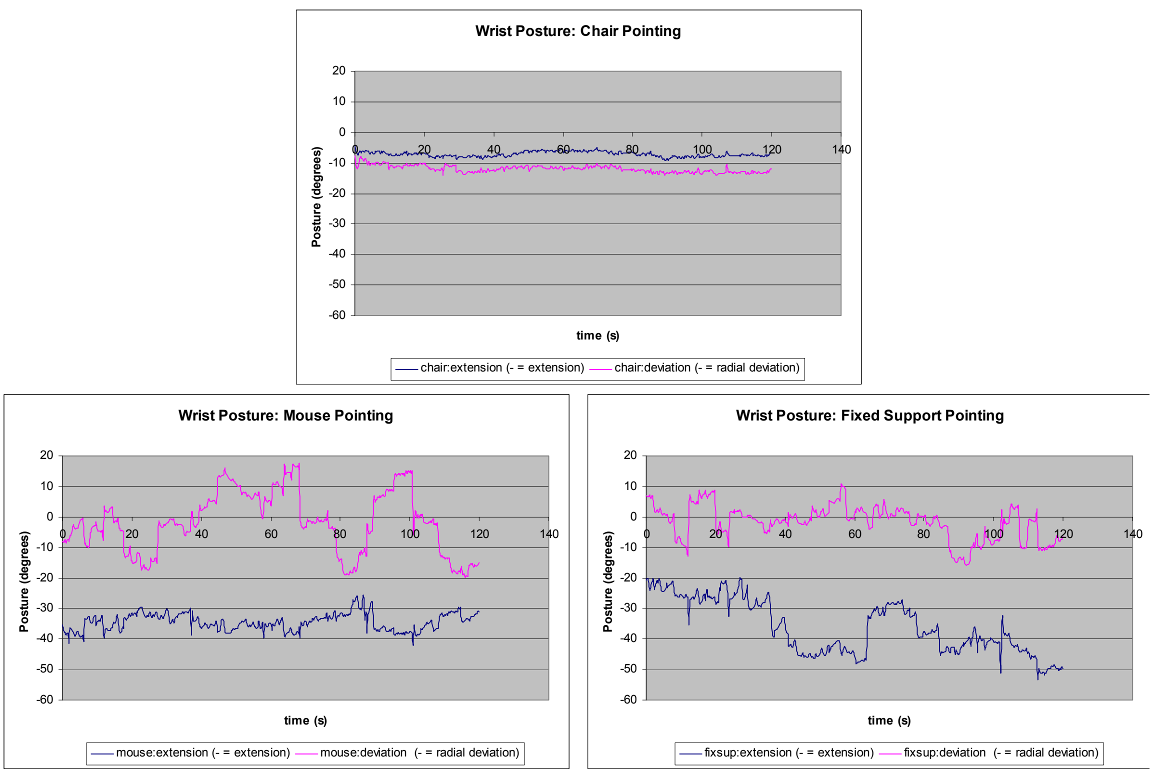




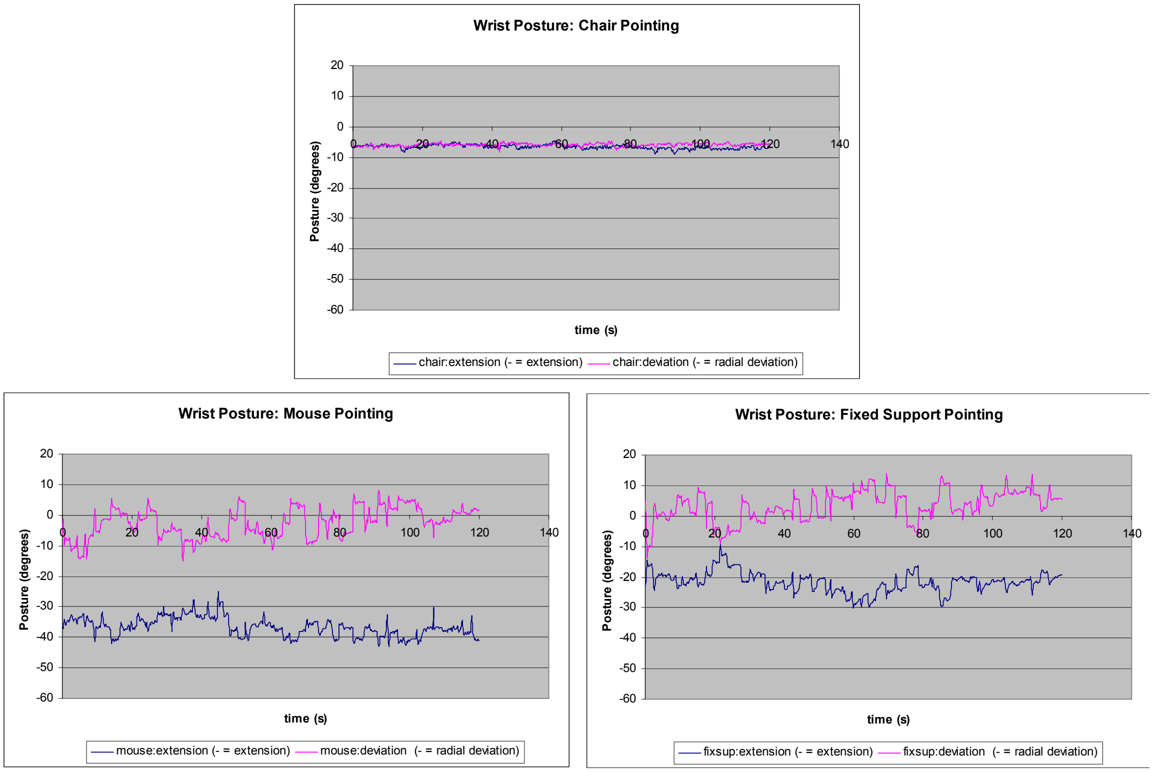
User 7 Wrist Posture Graphs – Pointing Block 6



User 8 Wrist Posture Graphs – Pointing Block 6

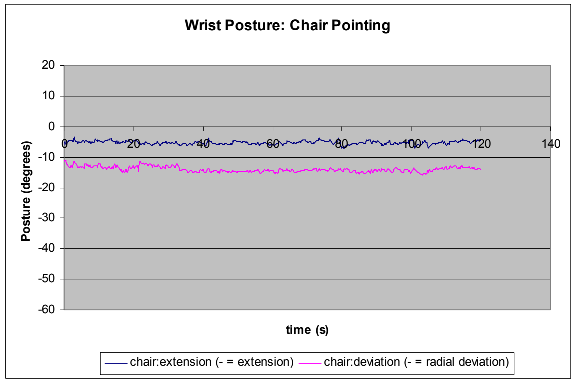


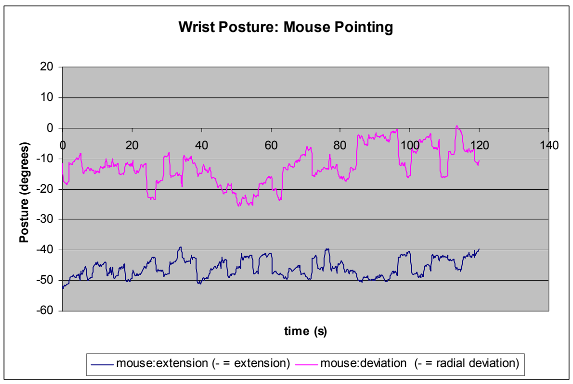
User 9 Wrist Posture Graphs – Pointing Block 6

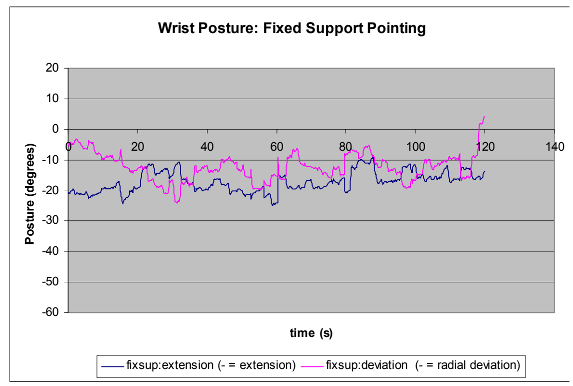


User 10 Wrist Posture Graphs – Pointing Block 6

User 11 Wrist Posture Graphs – Pointing Block 6







User 12 Wrist Posture Graphs – Pointing Block 6

Appendix C: One and Two-Handed Command Selection Technique Comparison (Chapter 6) Support Documents

This appendix includes the documentation and Committee for the Protection of Human Subjects (CPHS) approval letter for the Command Selection Method study described in Chapter 6. These documents provide the specific procedural details for this set of experiments as provided to CPHS. The subjective questionnaires used in this study are also provided.

C.1 Test Protocol

INVESTIGATOR:
Mr. Daniel L. Odell, Graduate Student
Department of Mechanical Engineering

FACULTY ADVISOR:
Prof. Paul Wright, Ph.D.
Department of Mechanical Engineering

1. TITLE: "Two-Handed Computer Interfacing – AmbiCAD"

2. RELATED PROJECTS: none

3. NATURE AND PURPOSE: The objective of this study is to determine how throughput, learning rates, and error rates compare for six different methods of computer interfacing. These measurements will be made using a new computer program, "AmbiCAD GL," which presents target shapes (lines, rectangles, ellipses, and splines) for the user to draw using a variety of techniques. The techniques include one-handed methods (standard toolbars, and standard marking menus), and two-handed methods (mapped hotkeys, grouped hotkeys, toolglass, and bimanual marking menus). Upon completion of the tests, users will be given a questionnaire asking for their subjective opinions of the input methods for consideration in future design revisions.

4. SUBJECTS: Ten to twelve computer-literate subjects will be recruited from the Department of Mechanical Engineering. All proposed subjects will be over 18 years of age.

5. RECRUITMENT: Subjects will be solicited from Prof. Wright's weekly seminar. The details of the study will be announced during the first 5 minutes of the seminar, and screening questionnaires will be handed out to interested individuals.

The following statement will be made at the beginning of class: "Hello everybody. My name is Dan Odell, and I am a 4th year student in Mechanical Engineering. I am currently preparing to run an experiment to examine ways in which people might use two hands simultaneously to interface with a computer. I'm looking for 10-12 volunteers to help me with this test. The experiment will require roughly 2 ¼ hours of time. So, if you're interested in participating in an exciting experiment and checking out a new type of computer interface, please raise your hand and I'll give you a screening questionnaire. I'll collect the forms at the end of class. Thank you."

6. SCREENING PROCEDURES: Ten to twelve subjects who use a computer with a mouse on a daily basis with their right hand will be selected. Computer users with more experience, and who use more pointing-based applications are considered to be more desirable. In addition, potential subjects with any upper body injuries (particularly repetitive strain injuries) or disabilities will be disqualified from the study. All screening questionnaires for subjects screened out of the study will be destroyed.

7. PROCEDURES: At the beginning of the testing session, before any testing begins, subjects will be asked to read and sign the Informed Consent form. Next, as described by the Informed Consent form, subjects will be asked to draw shapes (lines, rectangles, and ellipses) to match targets presented by AmbiCAD. The shapes will be drawn using six different methods of input, each using a mouse in either one hand or both hands. Each input method is expected to take roughly 15 minutes to test, in addition to 3 minutes to read instructions for each method. Participants will be given a break (~4 mins.) between each task. In addition, subjects may take a short rest anytime they desire between target shapes. After all tests are completed, the subjects will be given a short questionnaire asking for their opinions of the different input methods. The total task time is expected to be about 2 ¼ hours per subject. Testing will take place in 2111 Etcheverry Hall.

8. BENEFITS: There are no foreseeable direct benefits to the subjects. However, the study will provide valuable information about the nature of bimanual computer interfacing, which may lead to improved computer interfaces in the future.

9. RISKS: There are no known risks for subjects performing this experiment.

10. CONFIDENTIALITY: Subjects will be issued code numbers upon acceptance to the study. When compiling data, subjects will be referred to only by code number. At the conclusion of the test, the screening questionnaires, which identify participants, will be destroyed. During the study, screening questionnaires will be stored separately from testing data.

11. INFORMED CONSENT: The subjects will be given the consent documents to read and sign at the initial meeting, after the screening process.

12. FINANCIAL ASPECTS: None.

13. WRITTEN MATERIALS: Please find attached a copy of the post-test questionnaire, the screening questionnaire, and the testing instruction set.

C.2 Informed Consent Form

My name is Dan Odell, and I am a graduate student in the Mechanical Engineering Department at the University of California at Berkeley. I am currently performing a study to examine different ways in which people may use two hands simultaneously to interface with a computer. For the purposes of this research, I am asking people to draw shapes (lines, rectangles, and ellipses) to match targets presented by the computer program AmbiCAD GL. The shapes will be drawn using six different methods of input, each using a mouse in either one hand or both hands. Each input method is expected to take roughly 15 minutes to test, in addition to 3 minutes to read instructions for each method. After all tests are completed, I will give a short questionnaire asking for your opinions of the different input methods.

There will be a break between each task. The total task time will be approximately 2 hours and 15 minutes.
Any information that is obtained in connection with this study that can be identified with volunteers will remain confidential and will be disclosed only with their written permission. The Screening Questionnaire that subjects have filled out will be destroyed at the end of the study. Computer data and Post-test Questionnaires will be kept, but will be identified only by a code number. There will be no means of linking subject's names to the number.

During the course of the study, if you find the task too fatiguing, or if you feel eyestrain, you can pause for a break. Your participation is entirely voluntary, and you can discontinue your participation at any time.

There are no known risks to subjects from taking part in this research, and no direct benefits either. However, it is hoped that the research will benefit researchers with better understanding of human-computer interfacing.

If you have any questions about the research, you can call me, the director of the research study, Dan Odell, at 643-6546, or contact me at dano@kingkong.me.berkeley.edu.

Your signature below indicates that you have read and understood the information provided above, that you willingly agree to participate, that you consent to the use of data gathered during the course of this study and through the screening questionnaire, and that you may withdraw your consent at any time and discontinue participation at any time, and that you will receive a copy of this form upon request. If you have any question regarding your treatment or rights as a participant in this research project, please contact the University of California at Berkeley's, Committee for Protection of Human Subjects at 510/642-7461, subjects@uclink.berkeley.edu.

I have read this consent form and agree to participate in this research.

Signature ______________________________________ Date ________________

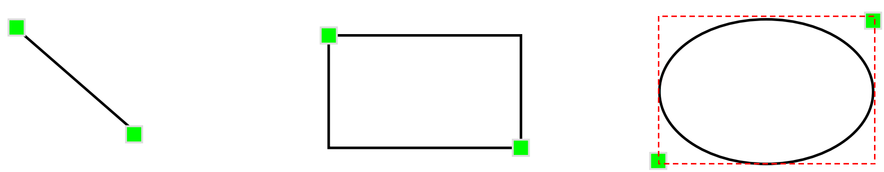
C.3 Participant Instruction Set

Drawing Shapes Using AmbiCAD GL

The objective of this study is to determine how throughput, learning rates, and error rates compare for six different methods of computer interfacing. These measurements will be made using a new computer program, "AmbiCAD GL," which presents target shapes (lines, rectangles, and ovals) for the user to draw using a variety of techniques. The goal is for the user to draw a new shape that matches the target shape as *quickly as possible, while maintaining a high level of accuracy (<10% error rate)*. The techniques include one-handed methods (standard toolbars, and standard marking menus), and two-handed methods (mapped hotkeys, grouped hotkeys, toolglass, and bimanual marking menus). Upon completion of the tests, users will be given a questionnaire asking for their subjective opinions of the input methods for consideration in future design revisions.

Shape drawing in AmbiCAD Gl is accomplished by first selecting the desired shape (using one of the six input techniques), and then specifying the two shape control points. After the first control point is specified*, the right mouse's left button must be held down*. The second control point is specified when the left button is released. The *right* mouse is always used to specify shape control points. The left mouse (when used) is used to select the desired tool, and its buttons are never used.

The control point specification follows the convention of Microsoft Paint (see Figure 1). For a Line, the control points are simply the endpoints of the line. For a rectangle, the control points are the two opposing corners of the rectangle. The oval control points specify an imaginary bounding box that is tangent to the oval. Note that while AmbiCAD presents the option to draw splines, no splines will be used in this experiment.



a) Line b) Rectangle c) Oval

Figure 1: Shape Control Points

Please run each input method for eight sessions, following the order marked next to the input method description on this instruction sheet. AmbiCAD will automatically close at the end of each session (24 trial shapes), and must be restarted after every session. Make sure to maximize the AmbiCAD window at the start of every session. Take a short break (~4 mins.) between input methods. Additionally, you may take a brief rest anytime you desire between target shapes. After mastering the use of the six input methods, please run final trials for Toolbar and Toolglass without homing, using these methods to draw randomly presented shapes without the homing screen.

If something extraneous to the test affects your drawing time (such as a sneeze), intentionally draw the target shape incorrectly to register an error, and note the event next to the instruction sets below.

Standard Toolbars

Standard toolbars represent the existing standard for command selection. A toolbar is presented in a fixed position in the upper-left corner of the screen (see Figure 2). The desired shape is selected by left-clicking with the right mouse in the toolbar box that corresponds with the desired shape. Once the shape is selected, draw the shape by specifying the control points, following the first section of this instruction set.

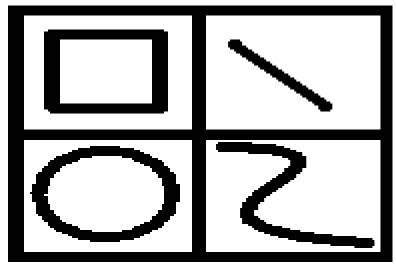


Figure 2: Toolbar

Please run AmbiCAD GL eight times using the standard toolbar input method. Check each run box at the completion of each run.

Standard Toolbar Run			
1	2	3	4
5	6	7	8

Toolglass

The toolglass input method utilizes the standard rectangular toolbar. However, instead of being fixed in the upper-left corner of the workspace, the position of the toolbar is controlled by the left hand. In addition, rather than specifying a shape and then specifying the first control point sequentially, the desired shape and first control point are specified simultaneously by left-clicking *through* the toolglass and onto the workspace. The left-mouse button must then be held down as the second control point is specified upon the release of the left-mouse button. Both mice can be moved simultaneously.

Please run AmbiCAD GL eight times using the toolglass input method. Check off each run box at the completion of each run.

Toolglass Run			
1	2	3	4
5	6	7	8

Standard Marking Menus
Marking Menus represent an input method that presents the toolbar directly under cursor - similar to the pop-up menus available under the right mouse button in Windows. They also provide an excellent opportunity to provide faster input with learning. This is done by only presenting the menu after a fixed amount of time. Users who have memorized the radial position of the menu elements can enter commands immediately (before the menu appears), allowing for rapid input without cluttering the work area with toolbars.

To use this input method, click and hold the right mouse left-button anywhere on the screen, preferably somewhat near the control points of the target shape. With the button held, move the cursor up, down, left, or right to the corresponding shape you wish to draw (see Figure 3). The shape is selected once the cursor crosses the menu boundary on the marking menu. Once the shape is selected, draw the shape by specifying the control points, following the first section of this instruction set.

As you become more familiar with the shape positions on the marking menu, remember that you can enter commands *before* the menu appears. To do this, simply move the cursor to the memorized command location with the left-button held down. As the test proceeds, try to memorize the command locations and issue commands before the pop-up menu appears.

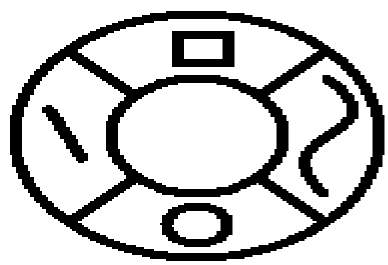


Figure 3: Marking Menu – Radial Command Entry

Please run AmbiCAD GL eight times using the standard marking menu input method. Check off each run box at the completion of each run.

<table>
<tr><td colspan="4">Standard Marking Menu Run</td></tr>
<tr><td>1</td><td>2</td><td>3</td><td>4</td></tr>
<tr><td>5</td><td>6</td><td>7</td><td>8</td></tr>
</table>

Bimanual Marking Menus
Bimanual marking menus are similar to standard marking menus, except that they use the left mouse to select the desired shape, and the right mouse to specify the shape control points. The selection is initiated by left clicking and holding on one of the desired control points with the right mouse. As the left button is held on the right mouse, a blue dotted line will appear to follow the motions of the right mouse. This blue line represents the line specifying the shape control points. The second control point is specified when the left mouse button is released.

Simultaneously, a yellow dotted line will appear that is controlled by the left mouse. This yellow line is the marking line that is used to select the desired shape. The shape command is specified when this line crosses the boundary of the desired command on the marking menu. Once the desired shape is specified, the blue and yellow dotted lines will disappear, and will be replaced by a stretchable version of the specified shape. Note that both lines can be controlled simultaneously, and the commands don't need to be issued sequentially.

As in standard marking menus, the menu (Fig. 3) will appear a short while after the left-mouse button is held, providing visual feedback about the location of each shape command. However, as the command locations are memorized, the left-hand can be moved to specify the shape *before* the menu appears. As the test proceeds, try to memorize the command locations and issue commands before the pop-up menu appears.

Please run AmbiCAD GL eight times using the bimanual marking menu input method. Check off each run box at the completion of each run.

Bimanual Marking Menu Run			
1	2	3	4
5	6	7	8

HotKeys

HotKeys are currently the most commonly used method of two-handed input. Using this method, control points are specified with the right mouse, while the desired shapes are selected through keys on the keyboard with the left hand. In AmbiCAD, the desired shape must first be specified using the keyboard commands, and then the shape is drawn normally as described in "drawing shapes." Hotkeys come in two flavors:

Mapped Hotkeys

"Mapped hotkeys" are hotkeys where the name of the key is related to the name of the command. For example, using mapped hotkeys in AmbiCAD GL, the command to draw a **R**ectangle is entered using the "R" key. See figure 4 for the remaining mapped hotkeys command designations. Refer to this figure while learning to use this input method. Do not stretch your hand to cover all of the mapped hotkeys (effectively changing them to grouped hotkeys). Instead, keep your left hand in the home position, moving it only when necessary.
Please run AmbiCAD GL eight times using mapped hotkeys. Check off each run box at the completion of each run.

Mapped Hotkeys			
1	2	3	4
5	6	7	8

Grouped Hotkeys

"Grouped hotkeys" are hotkeys where the most commonly used commands are grouped closely together to minimize the need to change hand positions. For example, using grouped hotkeys in AmbiCAD GL, all of the commands are entered by typing in the digits 1 to 4. See figure 4 for the remaining grouped command designations. Refer to this figure while learning to use this input method.
Please run AmbiCAD GL eight times using grouped hotkeys. Check off each run box at the completion of each run.

Grouped Hotkeys			
1	2	3	4
5	6	7	8

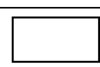
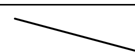
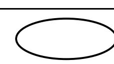
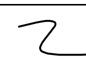
Shape	**Rectangle**	**Line**	**Oval**	**Spline**
Shape				
Mapped Hotkeys	**R**	**L**	**O**	**S**
Grouped Hotkeys	**1**	**2**	**3**	**4**

Figure 4: HotKey Designations

C.4 Post-test Questionnaire

1) Which of the input methods did you find to be the easiest to learn?

2) Which of the input methods did you find to be the most intuitive?

3) Which of the input methods did you find to be the fastest?

4) Did you find any of the two-handed motions distracting? If so, please explain.

5) Which of the input methods most allowed you to move both hands simultaneously?

Overall Preference

6) Please rank the input methods in order of you preference.

	Least Favorite					*Most Favorite*
Standard Toolbar	x	x	x	x	x	x
Toolglass	x	x	x	x	x	x
Marking Menu	x	x	x	x	x	x
2-hand Marking Menu	x	x	x	x	x	x
Mapped Hotkeys	x	x	x	x	x	x
Grouped Hotkeys	x	x	x	x	x	x

7) Why did you select you most and least favorite as such?

8) Would you have preferred to use a different input device with your left hand?

9) What other applications do you think might benefit from these input methods?

10) Which input method was physically the most comfortable to operate?

11) Do you have any suggestions for improving any of the input methods?

C.5 CPHS Acceptance Letter

BERKELEY: COMMITTEE FOR PROTECTION
OF HUMAN SUBJECTS
101 WHEELER HALL, MC #1340
642-7461 * FAX: 643-6272
subjects@uclink4.berkeley.edu

June 18, 2003

MR. DAN ODELL
Department of Mechanical Engineering
2111 Etcheverry Hall

Re: "Two-Handed Computer Interfacing – AmbiCAD" – Graduate Research

The Project referred to above was given an approval in an expedited manner by the Committee for Protection of Human Subjects on Tuesday, June 17, 2003.

The number given to this project is 2003-8-8. Please refer to this number in all future correspondence.

The expiration date of this approval is June 11, 2004. Approximately six weeks before the expiration date, we will send you a continuation/renewal request form. Please fill out the form and return it to the Committee, according to the instructions. If you do not receive these forms in a timely manner, please contact the CPHS Office at (510) 642-7461, or visit our website at http://cphs.berkeley.edu.

Attached is a copy of the consent materials reviewed by the Committee; the expiration date of the Committee's review of this form is noted on it. Please copy and use this stamped consent form for the coming year.

Please note that even though the Committee has approved your project, you must bring promptly to our attention any changes in the design or conduct of your research that affect human subjects. If any of your subjects experience any untoward events in the course of this research, you must inform the Committee within ten (10) working days.

If you have any questions regarding this matter, please contact the CPHS staff at 642-7467, FAX 643-6272, e-mail: adelphia@uclink4.berkeley.edu.

Sincerely,

Jane Gilbert Mauldon

Jane Gilbert Mauldon
Chair, Committee for Protection of Human Subjects
Associate Professor, Goldman School of Public Policy

cc: Professor Paul Wright
Graduate Division (SID #11226113)

JGM:amb

UNIVERSITY OF CALIFORNIA (Letterhead for Interdepartmental Use)

C.6 Compiled Questionnaire Results

				user 1	user 2	user 3	user 4	user 5	user 6	user 7	user 8	user 9	user 10	user 11	user 12
Learning	out of 11		**Which of the input methods did you find to be the easiest to learn?**												
		5	Standard Toolbar		1		1	1	1					1	
		4	Grouped Hotkeys		1	1					1		1		
		2	Bimanual Marking Menus			1					1				
		2	Mapped Hotkeys							1					1
		1	Marking Menus									1			
	out of 12		**Which of the input methods did you find to be the most intuitive?**												
		6	Grouped Hotkeys	1	1	1	1				1		1		
		5	Standard Toolbar		1				1	1				1	1
		2	Bimanual Marking Menus			1		1							
		1	Hotkeys		1										
		1	Marking Menus									1			
Practiced Skill	out of 12		**Which of the input methods did you find to be the fastest?**												
		8	Grouped Hotkeys	1	1	1	1	1		1	1		1		
		5 or 6	Bimanual Marking Menus	1	1	?			1		1			1	
		1	Marking Menus									1			
		1	Mapped Hotkeys												1
	out of 12		**Did you find any of the two-handed motions distracting? If so, please explain.**												
		9	Toolglass	1	1	1		1		1	1	1		1	1
		1	Bimanual Marking-menu										1		
		2	None				1		1						
	out of 12		**Which of the input methods most allowed you to move both hands simultaneously?**												
		9	Bimanual Marking Menus	1	1	1	1	1	1	1		1		1	
		3	Toolglass		1						1				1
		1	Grouped Hotkeys										1		
	out of 11		**Which input method was physically the most comfortable to operate?**												
		4 to 6	Bimanual Marking Menus		1	1	1	?	1			1			?
		3	Standard Toolbar		1			1			1				
		3	Grouped Hotkeys							1			1	1	
		3	Marking Menu		1			1							1
		1	Toolglass												1
			Would you have preferred to use a different input device with your left hand?												
		5	Joystick		1		1	1			1	1			
		2	"keyboard"/Arrow keys										1	1	
		1	"hatswitch" on dominant hand to *replace* non-dominant hand	1											
		1	Touchpad					1							
		1	Trackball			1									
		1	"yes"						1						
		2	None							1					1
			What other applications do you think might benefit from these input methods?												
		4	Games	1					1	1		1			
		3	2D Graphics Apps	1		1									1
		3	CAD			1						1		1	
		1	3D Animation	1											
		1	Powerpoint		1										
		1	Excel								1				
		1	Radiology/Body Imaging				1								
		1	"Anything with repeated commands"					1							
		1	Apps with lots of options										1		
		1	Anything non-text									1			
		1	Web browsing									1			
			Do you have any suggetions for improving any of the input methods?												
		4	Selection error recovery (marking menus)	1					1				1	1	

			user 1	user 2	user 3	user 4	user 5	user 6	user 7	user 8	user 9	user 10	user 11	user 12
Favorites	1(least) to 6(most)													
		Standard Toolbar	3	2	2	1	3	5	4	4	2	5	2	5
		Toolglass	1	1	1	2	1	3	1	1	1	1	1	1
		Marking Menu	5	4	4	4	5	2	2	2	6	3	4	3
		2-hand Marking Menu	6	5	6	6	6	6	5	6	5	4	6	2
		Mapped Hotkeys	2	3	3	3	2	4	3	3	3	2	3	6
		Grouped Hotkeys	4	6	5	5	4	1	6	5	4	6	5	4
Standard Toolbar														
		postitive comments												
		negative comments												
	1	More moving and clicking				1								
Hotkeys														
		postitive comments												
	1	natural												1
		negative comments												
Grouped Hotkeys														
		postitive comments												
	3	fast		1					1			1		
	3	easy/fast to correct mistakes			1						1	1		
	1	comfortable							1					
	1	natural gaming motion		1										
	1	easy to use										1		
		negative comments												
	1	won't scale	1											
	1	hard to remember keys						1						
Toolglass														
		postitive comments												
		negative comments												
	7	split focus/distracting	1		1				1	1	1	1		1
	4	annoying/frustrating/pain to use		1	1		1				1			
	4	difficult/hard to control					1			1			1	1
	3	sluggish/slow		1			1						1	
	2	too precise/sensitive (non-dominant hand)				1						1		
	1	too much freedom		1										
	1	not intuitive			1									
	1	too much thinking								1				
	1	selection should be persistent									1			
	1	errors hard to correct										1		
Marking Menu														
		postitive comments												
	1	"...let me set the ref point and select the tool quickly"									1			
		negative comments												
	1	needed "line"	1											
	1	repetitive (compared to bimanual marking menu)					1							
	1	selection should be persistent		1										
	1	need error recovery										1		
Bimanual Marking Menu														
		postitive comments												
	5	fast/efficient	1			1		1		1			1	
	1	fun			1									
	1	easy to use			1									
	1	like an extension of myself					1							
		negative comments												
	3	needed selection error recovery	1					1				1		
	1	easy to select wrong command										1		
	1	too much freedom										1		

C.7 Raw Quantitative Data

Error Rates		Toolbar		Hotkeys Grouped		Hotkeys Mapped		Marking Menus		Bimanual Marking Menus		Toolglass	
	Block #	Oval Error	Total Error	Oval Error	Total Error	Oval Error	Total Error	Oval Error	Total Error	Oval Error	Total Error	Oval Error	Total Error
user1	1	0	0	3	3	1	2	2	3	1	1	3	3
	2	2	3	2	2	1	1	5	5	2	4	1	1
	3	1	2	1	2	3	3	2	3	1	1	1	2
	4	2	2	0	0	2	2	3	3	4	4	0	2
	5	0	0	1	1	0	0	3	3	2	2	0	0
	6	2	2	1	1	1	1	4	4	2	4	0	2
	7	0	0	1	2	1	1	3	3	2	2	1	2
	8	2	2	1	1	1	1	2	3	3	4	2	3
user2	1	5	8	2	4	2	3	4	9	2	4	2	3
	2	3	4	0	1	2	2	6	7	3	4	3	3
	3	7	7	1	2	3	3	4	4	1	4	2	2
	4	4	4	0	0	0	1	6	7	1	3	2	3
	5	3	3	2	3	1	2	5	5	3	3	1	1
	6	5	5	3	3	2	2	3	3	1	1	2	2
	7	1	2	1	1	2	2	5	5	2	4	3	3
	8	3	4	1	1	0	0	3	3	4	5	1	1
user3	1	0	1	3	4	1	1	1	1	2	3	1	1
	2	0	0	1	2	2	2	2	2	1	1	1	1
	3	1	3	1	2	1	1	1	2	0	0	2	2
	4	0	1	1	1	1	1	2	3	2	3	1	1
	5	1	2	0	1	1	1	0	1	0	0	2	2
	6	1	1	0	0	1	1	1	1	0	0	0	0
	7	1	2	1	1	1	1	2	2	0	0	3	3
	8	1	2	3	3	0	0	1	3	0	1	1	1
user4	1	1	1	0	1	0	0	1	2	0	3	0	0
	2	1	1	0	0	1	1	0	2	0	3	3	3
	3	0	1	2	2	0	0	0	0	2	3	0	0
	4	0	0	2	2	1	1	0	2	2	2	1	1
	5	0	0	1	2	1	1	0	0	1	1	1	1
	6	1	1	3	3	0	0	1	3	0	0	0	0
	7	2	2	1	1	1	1	0	1	1	1	1	1
	8	1	2	1	1	0	0	0	3	2	3	0	0
user5	1	1	1	1	3	3	4	2	3	2	3	5	6
	2	2	2	0	0	2	3	2	3	2	4	4	4
	3	2	3	1	2	2	2	1	2	0	0	2	2
	4	1	2	3	3	1	1	2	2	4	4	2	3
	5	1	1	2	2	3	3	1	1	1	4	2	3
	6	2	4	1	2	2	2	2	2	0	1	3	3
	7	1	2	0	1	1	1	1	2	0	1	5	5
	8	1	1	1	1	0	0	0	1	1	2	3	3
user6	1	1	1	1	1	1	1	2	7	3	5	1	1
	2	2	2	1	2	1	1	1	1	0	2	0	0
	3	0	0	0	0	1	2	0	0	0	2	1	2
	4	0	0	1	2	0	0	0	0	1	2	0	0
	5	1	2	0	1	1	1	1	1	0	1	0	1
	6	1	1	1	1	0	0	0	0	0	2	0	1
	7	0	3	1	2	0	1	1	1	1	1	2	2
	8	1	2	0	0	0	0	0	0	0	2	0	1
user7	1	1	1	3	4	3	4	2	3	1	1	1	1
	2	1	2	1	1	1	1	1	2	2	2	2	2
	3	1	2	1	1	2	2	1	2	2	3	1	1
	4	0	0	2	2	0	1	0	0	2	5	3	3
	5	0	2	0	0	0	1	0	2	2	3	2	3
	6	3	6	0	0	3	4	0	0	2	3	1	2
	7	0	0	0	0	1	1	1	2	1	3	3	4
	8	2	3	2	3	0	0	0	0	2	3	2	3
user8	1	1	2	0	0	1	1	1	3	1	2	1	1
	2	1	2	0	0	0	0	0	0	4	6	2	2
	3	2	3	0	1	0	0	0	2	0	1	1	1
	4	2	3	1	1	0	0	2	4	1	2	2	2
	5	1	1	1	1	0	0	1	4	1	2	3	3
	6	3	4	0	1	0	0	0	1	1	1	1	1
	7	3	3	1	1	0	0	0	2	1	1	0	1
	8	1	1	0	2	1	2	1	3	1	1	4	4

Error Rates

user9	1	3	4	3	4	2	3	3	3	3	4	6	8
	2	4	6	2	3	2	2	3	4	2	2	4	5
	3	1	4	0	0	1	2	1	4	3	4	2	4
	4	1	1	3	3	4	6	0	3	3	4	2	2
	5	3	4	1	2	0	1	0	1	3	6	5	5
	6	3	5	1	1	4	4	2	5	3	6	1	2
	7	2	3	2	3	3	3	3	5	2	3	3	3
	8	1	2	1	1	4	4	2	5	0	1	1	1
user10	1	2	3	1	2	2	2	3	7	1	2	2	2
	2	1	3	2	2	1	1	2	4	2	2	4	4
	3	2	4	1	3	1	1	1	1	1	4	3	3
	4	1	3	4	6	2	2	1	1	1	1	2	3
	5	2	2	2	2	2	2	1	1	5	8	1	1
	6	2	3	1	2	2	2	1	3	1	4	2	2
	7	0	0	1	2	2	2	1	4	0	2	1	1
	8	1	4	0	3	2	2	0	2	3	8	2	2
user11	1	2	4	2	2	1	1	2	3	0	2	1	1
	2	0	0	0	0	2	2	0	0	0	2	0	0
	3	3	3	1	1	0	0	0	0	0	2	1	1
	4	3	4	1	1	0	0	1	1	0	1	0	0
	5	1	1	0	0	1	1	1	1	1	2	0	0
	6	2	2	1	2	1	1	2	3	1	3	3	4
	7	1	2	0	0	1	1	1	3	1	2	2	3
	8	1	2	2	2	4	5	0	0	2	3	1	1
user12	1	3	3	2	6	3	4	1	5	2	5	3	3
	2	2	4	5	11	0	0	0	2	3	4	2	2
	3	3	4	5	7	2	2	0	1	2	4	2	2
	4	3	5	5	5	2	2	0	1	0	1	1	1
	5	2	2	4	4	3	7	0	2	1	3	0	1
	6	4	4	4	5	4	4	0	0	2	3	1	1
	7	5	6	3	3	3	3	1	3	1	1	2	2
	8	2	3	3	4	1	1	0	0	2	5	0	0
		Toolbar		**Hotkeys Grouped**		**Hotkeys Mapped**		**Marking Menus**		**Bimanual Marking Menus**		**Toolglass**	
		TB	TB	HKG	HKG	HKM	HKM	MM	MM	BMM	BMM	TG	TG
Block #		Oval Error	Total Error	Oval Error	Total Error	Oval Error	Total Error	Oval Error	Total Error	Oval Error	Total Error	Oval Error	Total Error
Total trials	2304												
Non-Oval trials	1536												
Average		1.625	2.3958333	1.34375	1.9375	1.3125	1.5625	1.3645833	2.416667	1.427083	2.635416667	1.6666667	1.98958333
Total		156	230	129	186	126	150	131	232	137	253	160	191
Average % Tot.		6.77%	9.98%	5.60%	8.07%	5.47%	6.51%	5.69%	10.07%	5.95%	10.98%	6.94%	8.29%
Oval % for graph			6.77%		5.60%		5.47%		5.69%		5.95%		6.94%
StDev		1.331797361	1.6637255	1.246706	1.7339489	1.136129	1.3978367	1.4445527	1.861899	1.167497	1.66145017	1.3271788	1.45453767
StDev %		5.55%	6.93%	5.19%	7.22%	4.73%	5.82%	6.02%	7.76%	4.86%	6.92%	5.53%	6.06%
		0.16647467											
Oval/Total Error %		67.83%		69.35%		84.00%		56.47%		54.15%		83.77%	

Error Rates Continued

Toolbar		Mean Movement Time												Toolbar	
Block #	LN block	user1	user2	user3	user4	user5	user6	user7	user8	user9	user10	user11	user12	Grand Averages	StDev
1	0	4276.833	4267.9375	4849.13043	4532	3568.78261	3922.348	4057.3	3091.13636	3343.3	3506.5	4137.3	3544.05	3924.708907	522.86
2	0.693147181	3884	3462.55	5135.375	4069	3339.04545	3765.364	3492.4	3065.13636	3279.2	3230	4363.1	3664.2	3729.088905	579.66
3	1.098612289	4248.727	3344.117647	4949.14286	4550	3074.19048	3850.5	3575.4	3011.95238	3213.4	3467.9	4279.2	3793.75	3779.833857	615.85
4	1.386294361	3949.136	3333.4	4901.95652	4379	3303.40909	3740.792	3158.8	2875.57143	3002	3241.8	4051.7	3527.05	3622.030245	603.87
5	1.609437912	4038.625	3120.619048	4779.86364	4229	3237.04348	3583.682	3668.3	2772.91304	2837.7	3532	4245	3468	3626.05588	606.16
6	1.791759469	3749.364	3291	4972.78261	4155	3326.85	3883.304	3398.1	2622.25	2992.8	3333.2	4048.5	3436.75	3600.863663	612.76
7	1.945910149	3844.542	3456.409091	4882.86364	4041	3484.63636	3880.19	3158.1	2965.09524	3022.9	3495	3921.8	3422.61	3631.278289	529.01
8	2.079441542	3633	3178.7	4905.81818	4098	3587.86957	3519.955	3048.1	2913.69565	3151	3304.9	3948.6	3738.14	3585.613155	551.06
Averages		3953.028	3431.841661	4922.11661	4257	3365.22838	3768.267	3444.6	2914.71881	3105.3	3388.9	4124.4	3574.32	3687.434113	554.52
Time Learning % Block 7-8		8.55%	12.99%	2.02%	5.37%	-2.34%	3.89%	17.84%	4.55%	6.78%	-1.20%	7.63%	0.28%	5.53%	5.82%
Differences (within)		0.000914	0.005566799	0.00123143	3E-06	0.00619641	0.000268	0.0151	9.7016E-05	0.0002	0.0045	0.0004	0.00275		
Squares		0.007316	0.016877436	0.00040846	0.003	0.00054826	0.001516	0.0318	0.00206593	0.0046	0.0001	0.0058	7.9E-06		

ANOVA Total 6 Methods			Square Sums	DOFs	Mean Square	F ratio	F probability	
Mean Check	1.225857444	Mean	1.22585744	1	1.22585744	126.1701		
		Between Device	0.13390716	5	0.02678143	2.75645	0.02538584	probability that mean values of learning percantages are the sam
		Within Tests	0.64125024	66	0.00971591			
Total Check	2.001014839	Total	2.00101484	72				

Hotkeys Grouped		Mean Movement Time												Hotkeys Grouped	
Block #	LN block	user1	user2	user3	user4	user5	user6	user7	user8	user9	user10	user11	user12	Grand Averages	StDev
1	0	2991.429	3022.95	6155.65	3847	3231.80952	3693.174	3105.9	2930.83333	2225.7	4045.8	3270.5	4175.33	3558.022729	983.4
2	0.693147181	2733.364	2838.652174	4321.45455	3741	3077.5	3269.136	2986.3	2489.66667	2154.1	3621.9	3224.3	3669.62	3177.274045	599.67
3	1.098612289	4248.727	2865.909091	4183.09091	3481	3211	3536.333	3051.2	2488.43478	2494.9	2830.3	2966.7	3905.47	3271.943215	604.73
4	1.386294361	2309.208	2925.958333	3969.21739	3439	3076.42857	3449.545	2854.1	2417.73913	2222.1	2712.2	3013.8	3752.21	3011.768668	558.82
5	1.609437912	2484.043	2801.571429	3356.3913	3011	3210.04545	3313.826	2631.2	2346.69565	2287.4	2759.5	2905.8	3764.75	2906.053781	446.36
6	1.791759469	2531.87	2886.571429	3366	3537	2906.90909	3257.696	2764	2365.91304	2408.3	2304.4	2766.5	3402.11	2874.733457	431.55
7	1.945910149	2580.227	2981.130435	3379.95652	3636	3037.86957	3144.455	2757.2	2225.34783	2241.3	2279.7	2825.3	3412.86	2875.102457	478.16
8	2.079441542	2645.826	2773.521739	3243.95238	3415	3060.82609	3222.833	2846.9	2253.04545	2187	2346.6	2767.6	2992.75	2813.003298	400.65
Averages		2815.587	2887.033079	3996.96413	3513	3101.54854	3360.875	2874.6	2439.70949	2277.6	2862.6	2967.5	3634.39	3060.987706	493.05
Time Learning % Block 7-8		8.59%	1.61%	36.19%	7.05%	3.18%	8.62%	7.99%	17.39%	-1.09%	######	13.82%	19.06%	13.51%	12.89%
Differences (within)		0.002418	0.014158412	0.05143206	0.004	0.01066549	0.002388	0.003	0.00150864	0.0213	0.0685	1E-05	0.00308	StDev	
Squares		0.00738	0.00025881	0.13094487	0.005	0.00101142	0.007432	0.0064	0.03024745	0.0001	0.1575	0.0191	0.03632	0.128880822	

ANOVA HKG vs. TB Time Learning %			Square Sums	DOFs	Mean Square	F ratio	F probability	
Mean Check	0.217464729	Mean	0.21746473	1	0.21746473	21.74564		
		Between Device	0.03818381	1	0.03818381	3.818234	0.06352705	probability that mean values of learning percantages are the sam
		Within Tests	0.22000845	22	0.01000038			
Total Check	0.475656982	Total	0.47565698	24				

Hotkeys Mapped		Mean Movement Time												Hotkeys Mapped	
Block #	LN block	user1	user2	user3	user4	user5	user6	user7	user8	user9	user10	user11	user12	Grand Averages	StDev
1	0	3965.273	3513.428571	4206.43478	4153	4348.25	4332.348	4351.6	5094.91304	3216.2	3425.5	4079.6	3866.6	4046.102076	504.63
2	0.693147181	3526.391	3438.954545	4009.86364	4471	4112.19048	4061.043	3936.9	4006.54167	2865	3562.2	3778.5	3771.5	3795.024121	411.03
3	1.098612289	4248.727	3285.238095	3894.21739	4223	4043.31818	3602	3971.1	3774.08333	3032.7	3675.9	3919.1	3805.82	3789.615622	356.71
4	1.386294361	3436.318	3196.304348	4175	4729	4130.47826	3685.167	4169.9	3659.04167	2725.1	3435.9	4004.4	3115.68	3705.216646	561.68
5	1.609437912	3425.708	3160.863636	3766.69565	4043	4128.33333	3580.391	3828.6	3422.875	2640.4	3574.7	3849.5	3225.71	3553.876484	416.53
6	1.791759469	3332.13	2995.227273	3802.43478	4131	3973.86364	3647.333	3761.1	3523.29167	2665.5	3659.5	3519.3	3166.5	3514.730506	417.55
7	1.945910149	3108.391	3026.5	3936.34783	4192	4337.43478	3667.043	4022.7	3400.625	2360	3835.2	3536.3	3500.57	3576.884436	556.04
8	2.079441542	3180.13	3147.875	3526.625	4232	3843.25	3573	3913	3267.22727	2559.8	3579.7	3560.2	3111.74	3457.867154	440.46
Averages		3527.884	3220.548934	3914.70238	4272	4114.63983	3768.541	3994.4	3768.57483	2758.1	3593.6	3780.9	3445.51	3679.914631	411.8
Time Learning % Block 7-8		15.95%	11.09%	9.32%	2.24%	3.37%	13.76%	3.95%	26.49%	19.07%	-6.07%	9.80%	13.56%	10.21%	8.62%
Differences (within)		0.003293	7.75741E-05	7.8984E-05	0.006	0.00468754	0.001263	0.0039	0.02649127	0.0079	0.0265	2E-05	0.00112	StDev	
Squares		0.025441	0.012304292	0.0086918	5E-04	0.00113242	0.018947	0.0016	0.07016061	0.0364	0.0037	0.0096	0.0184	0.086157048	

ANOVA HKM vs. TB Time Learning %			Square Sums	DOFs	Mean Square	F ratio	F probability	
Mean Check	0.148685021	Mean	0.14868502	1	0.14868502	27.49979		
		Between Device	0.01314981	1	0.01314981	2.4321	0.1331441	probability that mean values of learning percantages are the sam
		Within Tests	0.11894892	22	0.00540677			
Total Check	0.280783751	Total	0.28078375	24				

Mean Movement Times

Marking Menu		Mean Movement Time												**Marking Menu**	
Block #	LN block	user1	user2	user3	user4	user5	user6	user7	user8	user9	user10	user11	user12	Grand Averages	StDev
1	0	5776.381	3302.066667	4228.52174	3681.27	3458.47619	3989.176	6335.2	5206.42857	2924.8	4715	4404.2	4718.84	4395.029658	1021.3
2	0.693147181	3990	3148	3747.54545	4017.09	3384.47619	3154.435	5127.3	3601.66667	2747.9	4183.1	3805	4034.91	3745.112846	616.02
3	1.098612289	4248.727	3004.4	4493.54545	3908.08	3203.59091	3371.792	4500.8	3204.86364	2944.4	4277.7	3683.4	4020	3738.433514	579.03
4	1.386294361	3951.857	2999.529412	3749.04762	3757.68	3226.81818	3210.375	4297	3057.25	2777.2	4223.7	3636.7	4034.39	3576.798474	509.22
5	1.609437912	3539.81	3131.947368	3426.13043	3718.33	3381.17391	2958.913	3359.3	2938.65	2512.2	4087.2	3708.2	3915.59	3389.785829	449.52
6	1.791759469	3086.55	3204.095238	3724	3393.48	3490.59091	3203.708	3331.5	2763.04348	2462.8	3764.6	3662.2	3417.21	3291.98187	386.01
7	1.945910149	3000.381	2847.736842	3490.40909	3514.09	3353.04545	3035.217	3409.5	2692.95455	2441.8	3614.7	3676.7	3270.76	3195.600538	390.48
8	2.079441542	2711.048	2986.619048	3350.33333	3664.81	3297.43478	2936.375	3121	2683.66667	2512.2	3545.4	3975.5	3501.96	3190.529413	443.03
Averages		3788.094	3078.049322	3776.19164	3706.85	3349.45082	3232.499	4185.2	3268.56545	2665.4	4051.4	3819	3864.21	3565.409018	445.28
Time Learning % Block 7-8		42.05%	9.30%	14.31%	6.84%	2.83%	14.95%	43.00%	38.21%	12.74%	######	6.09%	22.01%	19.29%	14.24%
Differences (within)		0.051798	0.009974975	0.00248212	0.01551	0.02709138	0.001888	0.0562	0.0357775	0.0043	1E-06	0.0174	0.00074	StDev	
Squares		0.176816	0.008654107	0.02047227	0.00467	0.00080132	0.022336	0.1849	0.14596347	0.0162	0.0368	0.0037	0.04844	0.142444409	

ANOVA MM vs. TB Time Learning %			Square Sums	DOFs	Mean Square	F ratio	F probability
Mean Check	0.369632714	Mean	0.36963271	1	0.36963271	31.21778	
		Between Device	0.11360264	1	0.11360264	9.594448	0.00525585 probability that mean values of learning percantages are the sam
		Within Tests	0.26049002	22	0.01184046		
Total Check	0.743725377	Total	0.74372538	24			

Bimanual Marking Menu		Mean Movement Time												**Bimanual Marking Menu**	
Block #	LN block	user1	user2	user3	user4	user5	user6	user7	user8	user9	user10	user11	user12	Grand Averages	StDev
1	0	2837.174	3119	3788.14286	5761.9	3842.2381	4286.789	4380.4	3227.72727	3675.7	3154.9	3190.5	4252.32	3793.069291	806.24
2	0.693147181	2331.45	2720.95	3561.6087	3730.24	3156.65	3113.5	3739.9	2574.33333	3152.3	2543.3	3172.4	3363.6	3096.682813	469.14
3	1.098612289	4248.727	2860.65	3503.58333	3650	3485.29167	3250.091	3313.4	2529.43478	2706	2494.1	2918.5	2892.55	3154.35491	517.62
4	1.386294361	2179.2	3058.619048	3255.95238	3942.41	3271.3	3219.636	3377.5	2486.72727	2578.1	2357.5	3106.8	3403.48	3019.763081	515.13
5	1.609437912	2456.227	2855.571429	2950.375	3641.48	3317.25	3516.13	3326.3	2440.18182	2497	2358.9	2964.9	3690.57	3001.234166	491.71
6	1.791759469	2172.15	2909.434783	3255.16667	3709.38	3086	2897.318	3283.2	2498.34783	2502.6	2483.5	2946.2	2906.86	2887.515774	424.86
7	1.945910149	2412.955	2927.25	2949.70833	3855.22	3343.08696	2803.435	3262.6	2249.26087	2927.1	2258.1	2979.5	2842.74	2900.920676	460.81
8	2.079441542	2348.4	2692.315789	2909.82609	3496.43	3189.13636	3138.591	3239.3	2261.78261	2584.7	2805.3	2860.2	2927.47	2871.111031	365.18
Averages		2623.285	2892.973881	3271.79542	3973.38	3336.36914	3278.186	3490.3	2533.47447	2827.9	2556.9	3017.4	3284.95	3090.581468	429.83
Time Learning % Block 7-8		8.45%	3.67%	20.15%	22.38%	6.84%	18.86%	20.07%	23.12%	19.21%	######	8.18%	24.11%	15.64%	7.22%
Differences (within)		0.005179	0.014330516	0.00203468	0.00454	0.00774436	0.001039	0.002	0.0055879	0.0013	0.0009	0.0056	0.00718	StDev	
Squares		0.007132	0.001347319	0.04061167	0.05008	0.00468046	0.035588	0.0403	0.05343875	0.0369	0.016	0.0067	0.05815	0.072190711	

ANOVA BMM vs. TB Time Learning %			Square Sums	DOFs	Mean Square	F ratio	F probability
Mean Check	0.268947519	Mean	0.26894752	1	0.26894752	62.53139	
		Between Device	0.06134396	1	0.06134396	14.26272	0.00103838 probability that mean values of learning percantages are the sam
		Within Tests	0.094622	22	0.004301		
Total Check	0.424913487	Total	0.42491349	24			

Toolglass		Mean Movement Time												**Toolglass**	
Block #	LN block	user1	user2	user3	user4	user5	user6	user7	user8	user9	user10	user11	user12	Grand Averages	StDev
1	0	4603.667	4388.619048	5411.13043	5690.21	4494.22222	5744.739	5756.9	4696.52174	4438.9	4324.4	4705.7	5169.43	4952.031956	564.94
2	0.693147181	4950.043	3828.333333	4946.56522	5228	4331	5367.875	4925.1	3910.86364	4018.1	4029.4	4546.3	4802.05	4573.633898	537.23
3	1.098612289	4248.727	3916.590909	5022.54545	5149.38	4296.31818	5530.091	4613.3	3754.30435	3803.2	4185.9	4690.4	4912.45	4510.266908	568.81
4	1.386294361	5038.045	3830.333333	5051.04348	5000.48	4724.09524	4409.917	4409.2	3598.72727	3759	4357.8	4734.8	4430.26	4445.315443	501.3
5	1.609437912	4807.667	3633.782609	4750.31818	4826	4249.57143	4597.391	4351.4	3701.33333	3784	4307.2	4364.4	4491.39	4322.039649	419.34
6	1.791759469	4604.318	3810.818182	5228.625	4765.17	4343.57143	4494.739	4349.4	3816.08696	3645.9	4419.1	4296.7	4078	4321.032053	444.48
7	1.945910149	4118.864	3575.142857	4780.33333	4349.35	3956.36842	3883.727	4431.3	3928.47826	3979	3994.6	4024.7	3793.64	4067.95229	319.14
8	2.079441542	4312.762	3509.043478	4984.91304	4331.04	4142.66667	4287.565	3914.1	3603.1	3897.5	3874.7	4082.3	3823.79	4063.624409	393.34
Averages		4585.512	3811.582969	5021.93427	4917.45	4317.2267	4789.506	4593.8	3876.17694	3915.7	4186.6	4430.7	4437.63	4406.987076	403.12
Time Learning % Block 7-8		11.94%	13.82%	5.63%	20.72%	8.03%	26.33%	22.13%	12.41%	6.51%	5.93%	12.32%	23.53%	14.11%	7.33%
Differences (within)		0.000471	8.18294E-06	0.00718804	0.00438	0.00369041	0.014948	0.0064	0.00028756	0.0058	0.0067	0.0003	0.00888	StDev	
Squares		0.01425	0.019105556	0.00316982	0.04295	0.00645367	0.06935	0.049	0.0154072	0.0042	0.0035	0.0152	0.05536	0.073278666	

ANOVA TG vs. TB Time Learning %			Square Sums	DOFs	Mean Square	F ratio	F probability
Mean Check	0.231403911	Mean	0.23140391	1	0.23140391	52.83035	
		Between Device	0.04415051	1	0.04415051	10.07972	0.00438399 probability that mean values of learning percantages are the sam
		Within Tests	0.09636291	22	0.00438013		
Total Check	0.371917335	Total	0.37191734	24			

Time Averages	**TB**	**HKM**	**HKG**	**MM**	**BMM**	**TG**
Block 1-2	3826.899	3920.563099	3367.64839	4070.07	3444.87605	4762.833
Block 7-8	3608.446	3517.375795	2844.05288	3193.06	2886.01585	4065.788
Time Learning Delta	218.4532	403.1873033	523.59551	877.006	558.860198	697.0446
% Improvement	5.53%	10.21%	13.51%	19.29%	15.64%	14.11%

Mean Movement Times Continued

(Standard Error)

StDev — **Toolbar**

user1	user2	user3	user4	user5	user6	user7	user8	user9	user10	user11	user12	Grand Averages	StDev
547.358	581.9549	742.632	487.9073	576.2461	483.029	1039.268	440.5718	497.7939	389.407	402.4802	586.925	564.6311478	177.763
525.7384	369.0689	983.396	485.4365	502.8931	340.25	517.1719	471.454	383.3598	416.08	730.3379	402.258	510.6203245	180.965
639.3202	442.3429	680.424	555.6121	411.5835	503.151	678.5152	390.2564	327.3428	414.013	454.2244	592.846	507.4692431	119.609
504.7651	361.2475	593.943	746.1836	348.7688	563.054	477.9409	421.8887	306.415	424.416	377.1528	645.421	480.9329627	133.895
463.7825	407.9113	650.501	477.3406	431.808	507.844	809.0576	402.1219	277.4829	520.477	490.6662	636.097	506.257498	138.445
551.6838	346.1539	865.523	493.42	431.1454	556.101	657.7559	364.4498	445.0498	422.374	494.4526	787.744	534.654378	161.977
503.1116	731.1407	885.627	523.6988	438.9991	554.909	437.7092	376.2581	382.5994	451.206	528.8279	373.606	515.6410236	153.347
427.3345	303.1741	892.213	500.0685	387.9915	331.834	430.3337	366.6462	531.44	556.823	700.9837	472.158	491.750001	166.756
Averages													
520.3868	442.8743	786.782	533.7084	441.1794	480.021	630.9691	404.2059	393.9355	449.349	522.3907	562.132	513.9945723	

StDev — **Hotkeys Grouped**

user1	user2	user3	user4	user5	user6	user7	user8	user9	user10	user11	user12	Grand Averages	StDev
756.5995	423.7448	1752.81	632.5461	475.4767	831.297	742.1177	559.2551	459.831	669.892	657.5882	1375.04	778.0164356	395.973
481.0676	404.0259	657.342	626.817	418.4187	566.529	738.6746	355.2834	240.5619	557.443	705.5206	564.144	526.3189423	150.166
319.6668	419.7158	1112.5	615.6035	494.2471	747.887	866.6947	583.3683	412.8964	403.855	434.001	523.033	577.7891975	229.523
354.8869	454.2449	887.969	574.8659	494.6371	723.485	701.8713	395.3584	367.3099	692.511	665.3038	764.836	589.7731802	174.869
542.1429	310.9583	394.15	415.4551	629.1643	907.213	497.3352	435.0915	339.354	453.232	640.3914	959.991	543.7064669	208.668
380.8249	443.6403	507.435	707.7489	355.8481	687.734	522.1866	367.9942	539.4445	431.755	416.9869	836.53	516.5106875	153.036
419.9352	515.9132	539.826	438.845	469.7279	693.172	506.3327	239.8046	302.5694	309.448	534.3001	817.261	482.261237	162.734
358.7819	455.5274	417.3	700.1776	350.9672	628.462	526.9784	304.5252	394.7532	222.548	495.2213	663.14	459.8651046	148.277
Averages													
451.7382	428.4713	783.667	589.0074	461.0609	723.222	637.7739	405.0851	382.09	467.585	568.6642	812.997	559.2801565	

StDev — **Hotkeys Mapped**

user1	user2	user3	user4	user5	user6	user7	user8	user9	user10	user11	user12	Grand Averages	StDev
818.4341	594.0291	605.861	676.7343	719.5057	979.351	1544.304	1450.235	593.4212	309.276	627.4383	847.323	813.8260251	359.835
542.6105	628.4631	548.362	1194.665	559.3974	1032.58	1093.439	595.9704	480.6837	420.709	382.2582	924.527	700.305484	281.4
631.6328	587.2487	580.491	816.5963	520.3231	833.097	1127.006	674.2328	669.7616	477.169	614.6099	906.101	703.1890841	185.491
530.0511	642.2544	916.7	1183.327	691.7471	864.768	1126.088	638.9479	624.9984	321.555	786.6119	391.07	726.5099863	264.339
529.8999	694.2009	612.406	770.7056	656.8129	840.679	830.0446	914.6006	452.6766	536.272	486.8005	549.351	656.2041234	153.554
585.9861	498.1415	565.565	720.5622	665.9473	832.832	948.4167	724.4032	387.2048	375.677	696.9216	609.961	634.3015386	168.604
453.1783	437.9551	681.936	583.9344	829.5768	791.629	1003.122	629.2067	438.2337	706.282	412.944	793.256	646.7712306	188.565
564.2607	635.2702	1518.24	608.1596	511.6962	945.79	839.8993	609.0206	430.5792	539.539	475.6361	598.325	689.7016995	298.79
Averages													
582.0067	589.6954	753.696	819.3356	644.3758	890.091	1064.04	779.5771	509.6949	460.81	560.4026	702.489	696.3511464	

StDev — **Marking Menu**

user1	user2	user3	user4	user5	user6	user7	user8	user9	user10	user11	user12	Grand Averages	StDev
1945.576	941.5709	768.001	649.1745	638.1344	479.46	1456.613	1475.788	638.8854	748.162	940.8958	951.995	969.5213249	436.899
753.8111	443.6949	663.623	649.2404	416.9188	489.649	1235.2	817.7421	796.0371	519.596	579.5329	629.002	666.1706497	222.539
735.0881	317.2287	4235.16	776.8248	501.7417	604.303	1118.041	659.604	517.7193	556.975	430.1552	630.638	923.6231662	1062.03
619.9482	468.2221	593.11	919.1539	542.2459	800.194	1083.94	687.5926	536.4763	529.622	483.071	796.594	671.6807082	191.787
593.0622	466.3988	459.263	662.9946	492.3699	384.44	532.7457	337.3669	308.8099	514.253	374.1362	741.343	488.9319845	130.845
352.3786	642.0087	715.291	624.3177	427.8776	354.995	508.0669	357.0158	339.6149	387.569	557.4343	452.988	476.6297366	130.67
433.0759	483.6564	503.014	515.3666	503.6291	481.992	684.5189	427.8644	320.0683	499.852	442.1004	385.067	473.3505115	87.902
363.8686	487.053	426.849	593.2629	579.7926	326.018	436.1834	347.0509	362.4149	514.977	744.5534	540.438	476.8718242	124.692
Averages													
724.601	531.2292	1045.54	673.7919	512.8387	490.131	881.9135	638.7531	477.5032	533.876	568.9849	641.008	643.3474882	

StDev — **Bimanual Marking Menu**

user1	user2	user3	user4	user5	user6	user7	user8	user9	user10	user11	user12	Grand Averages	StDev
730.9711	722.9758	591.007	2402.741	591.5796	1622.81	1432.086	1244.664	829.1329	550.382	582.4621	1327.58	1052.366517	569.325
369.2356	250.2168	660.564	614.1094	528.9805	1083.75	1271.037	387.7921	509.9419	294.463	576.588	987.919	627.8828994	324.319
317.7622	555.3579	638.335	623.8306	543.7925	757.408	748.8594	388.3801	413.5411	510.229	479.6759	646.948	552.0099398	138.314
279.268	496.509	562.934	748.7731	646.2353	653.632	649.9934	365.1789	746.6479	458.241	546.4381	767.881	576.8109461	155.488
351.3395	414.7432	730.179	634.8256	655.0718	1294.85	709.3298	256.9189	375.3497	370.5	428.8885	1002.06	602.0048926	305.085
234.0073	573.9948	657.85	641.1024	426.6009	599.874	902.8938	427.7159	401.9494	376.32	504.3466	749.714	541.3640117	183.58
388.969	560.6079	536.381	537.0518	645.4171	591.508	802.3103	325.1912	1503.831	283.561	333.6445	621.075	594.1290207	324.836
357.4432	332.2039	551.033	643.2837	604.586	718.315	548.3646	338.7969	487.5762	873.961	441.5068	678.734	547.9836625	166.863
Averages													
378.6245	488.3262	616.035	855.7147	580.283	915.268	883.1092	466.8298	658.4963	464.707	486.6938	847.739	636.8189862	

StDev — **Toolglass**

user1	user2	user3	user4	user5	user6	user7	user8	user9	user10	user11	user12	Grand Averages	StDev
1433.98	916.7113	1120.77	1147.233	1015.549	1689.12	1950.562	1327.868	1216.569	794.836	1122.081	1660.11	1282.948668	343.333
2141.715	616.9518	1152.66	1142.446	732.8742	1710.36	1490.785	690.9701	916.0961	568.362	1161.161	1353.31	1139.807426	478.232
1829.314	707.201	1143.16	1131.75	982.8136	2125.71	1291.459	677.4497	915.6903	604.146	1101.138	1082.27	1132.675178	451.001
2137.558	725.0764	1167.14	1074.894	1018.393	914.504	1478.384	662.7533	841.1262	1391.9	1282.168	1065.75	1146.638016	399.789
1755.884	601.0433	1231.78	853.8186	951.9621	1090.52	1542.462	663.3205	740.478	1034.98	1071.937	1166.05	1058.686098	341.618
1681.487	670.9303	1264.66	1094.523	717.2216	1497.73	1419.824	992.9566	982.9234	1117.16	1152.069	923.197	1126.222947	302.646
1538.145	615.7441	1109.83	1094.575	679.763	885.331	1380.097	776.7858	859.1472	934.217	878.5123	897.667	970.8178556	270.931
1833.029	648.5567	990.963	823.386	647.6615	1795.86	1072.878	567.9474	634.0632	754.445	871.8064	700.767	945.1138199	432.989
Averages													
1793.889	687.7769	1147.62	1045.328	843.2797	1463.64	1453.307	795.0064	888.2616	900.006	1080.109	1106.14	1100.363751	

Movement Times Standard Deviations