ASYMMETRIC TWO-HANDED INPUT FOR MODE SELECTION ON TOUCHSCREENS

by

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Abstract

Away from computers, most manual activities make use of both hands together. Consider how you chop vegetables, stir a pot, hammer a nail, or play a musical instrument; even in writing, the “off” hand plays a role in holding the work steady. However, current touchscreen interfaces, even though called “multi-touch”, rarely make effective use of more than one hand at a time.

We performed an experiment to compare user performance and preference with a novel two-handed interface and the standard one-handed interface of current touchscreen tablet devices. We found that, even though none of the participants had previously used a bimanual touch interface before, nearly all performed the task faster with the new interface, and most found it smoother and more enjoyable to use. Our results suggest that, in certain applications, bimanual interfaces should be considered when designing new software for touch-based devices.

List of Abbreviations and Symbols Used

α	Significance level—the value of p below which the null hypothesis will be rejected
CI	Confidence interval
df	Degrees of freedom
F	Test statistic of the ANOVA test
GUI	Graphical User Interface
$\mathbf{H_0}$	Null hypothesis
$\mathbf{H_a}$	Alternative hypothesis
M	Mean
p	The probability of obtaining a result equal to or more extreme than what was observed if the populations from which the samples were drawn were equal.
SD	Standard deviation
$\mathbf{T^+}$	Test statistic of the Wilcoxon signed-rank test
UI	User Interface
W	Test statistic of the Wilcoxon rank-sum test

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Chapter 1

Introduction

1.1 The rise of touchscreens

Over the past several years, we have seen large touchscreen surfaces go from being confined to labs and specialized environments to become commonplace consumer devices, thanks largely to a plethora of inexpensive tablet computers from a variety of manufacturers. One feature common to most of these devices is the support for "multi-touch"—the ability for the touch sensing layer to detect and track the touches from several different fingers at once. And yet, the user interfaces to these new devices have largely taken their cues from the mouse-based interfaces that came before: they are driven almost entirely by sequential single-finger taps and drags. In particular, although there are a few common "gestures" that use two or more fingers (such as the common *pinch* and *zoom* gestures), there are very few occasions (apart from "thumb typing") where users find any opportunities to use both *hands* at once on a tablet.

1.2 Two hands are better than one?

Away from computers, in most skilled manual activities, the reverse is generally true: our hands usually work together as a pair. Even though we may say that we are "left-handed" or "right-handed", in fact, *both* hands play roles in almost everything we do. Whether it be chopping vegetables, stirring a pot, hammering nails, or playing a musical instrument, so many of our skilled manual activities depend on each hand playing an important role, often in an asymmetric and supportive manner. Even in seemingly unimanual activities, such as writing, the "off" hand helps to provide a frame of reference within space for the opposite hand [7], such that it is often possible to do things without having to see one or both of our hands to know where they are.

Despite this apparent preference for performing activities with both hands, our computers rarely take advantage of our bimanual abilities. "Almost without exception (the keyboard being the most notable), computer input techniques are based on the use of one hand. This means that the everyday skills we have acquired both through evolution and through a lifetime of learning, for the most part simply cannot be used to interact with computers." [4, p. 11.1]

Of course, this is not a new observation. There is a large body of research looking at bimanual interaction techniques going back several decades, however, most of it has involved using multiple single-handed input devices, such as pairs of mice, or combinations of a mouse, stylus and touch. As discussed further in Chapter 2, this sort of mixing places the user's hands in separate kinaesthetic "spaces" and prevents them from working in a naturally supportive way, which can actually lead to *poorer* performance.

The multi-touch touchscreen may be the first widely available input device that allows both hands to operate within a shared kinaesthetic frame of reference. Additionally, with a touchscreen, object manipulations are more direct than in so-called "direct manipulation" interfaces where a mouse or other indirect input device is involved. With a touchscreen, the arbitrary mapping of scales between the space in which the user's hands operate and the output space presented on the display is eliminated.

1.3 Modal versus quasimodal interfaces

One of the consequences of restricting input to a single hand is the resulting linear style of input that typically relies on *latched* program modes. In order to perform an operation, a mode is selected through an on-screen button and stays in effect until cancelled or changed.

This type of interface has long been known to lead to an increased frequency of *mode errors*—instances in which a user performs an action thinking that the application is one mode when it is actually in a different one—and users often struggle to figure out how to cancel a mode selection when they discover their mistake [20][18, chpt. 3].

Conversely, when users are required to *actively* perform some action in order to maintain the mode—such as holding down a key or, in the case of a touchscreen, maintaining a touch on the screen—this *kinaesthetic feedback* serves as a reminder that the mode is active, resulting in far fewer mode errors [20]. It is also easier to to get out of the mode—one simply stops doing the action. Modes engaged in this manner have been variously referred to as *kinaesthetically held* [22], *user-maintained* [20], *spring-loaded* [11], or *quasimodal* [18, p. 55]. The first is perhaps most descriptive, but it is rather a mouthful, so the latter will be used throughout this work to mean the same thing, when no confusion would arise.

1.4 Motivation for research

As part of our prior work in developing a prototype touch-based visual programming environment [8], we experimented with an interface design that combined the bimanual and quasimodal design principles, where one hand was used to select modes and the other to perform manipulations within that mode. This design was informally tested with a small sample of potential users and the feedback was very positive. Even in its preliminary form, most of the users found the interface enjoyable to use and more efficient than traditional drag-and-drop or latching interfaces. However, the audience for that software is very limited and it was felt that a more rigorous usability study was required to validate the design. The study described in this thesis is a step toward fulfilling that need.

1.5 Bimanual quasimodal touch input: A study

To properly test the effectiveness of the interface with a broader population, a more focused experiment was devised, based on earlier studies of bimanual input techniques involving other types of input devices. The experiment involved a simple connect-the-dots task that effectively isolates the interaction technique from the application and does not require that participants have any previous experience in order to participate. The study compared user performance and satisfaction with a bimanual quasimodal input technique against the common unimanual latching-style touchscreen interface. Within the study conditions, users almost uniformly performed the task more quickly with the bimanual interface and also expressed a strong overall preference for the same, despite its being completely new to them. These results suggest that this interface design may be a promising alternative for certain types of applications, though there is further work to be done to fully document the applicability of the technique.

Chapter 2

Background

2.1 The Kinematic Chain

In his seminal work, "Asymmetric Division of Labor in Human Skilled Bimanual Action" [1987], Yves Guiard identified a class of activities that involve two hands working together, but playing different roles; and noted that, in fact, this *bimanual asymmetric* arrangement was the *norm*. Many activities that are commonly thought of as one-handed, such as writing, can be demonstrated to depend on the actions of both hands. (In writing, the "off" hand positions and stabilizes the paper, shifting it as it gets filled, so that the writing hand needs to move less, as demonstrated in one of Guiard's experiments.) Even in cases where the second hand seems to be uninvolved, such as in throwing darts, it cannot be *proven* that this hand is not playing some role in balance, providing a spatial reference, or some other unidentified function.

Guiard proposed replacing the concept of *manual preference* (that the use of one hand is favoured over the other) with that of *lateral preference*, denoting "one of the two possible ways of assigning two roles to two hands". One is not "left-handed" or "right-handed", nor is one hand necessarily superior to the other, but rather one tends to assign certain roles to the left hand and others to the right, and these roles may be complementary but different (*asymmetric*).

(To be clear, there are also *symmetric* bimanual actions where both hands perform the same role, such as lifting a heavy object or typing on a keyboard, but it is specifically asymmetric activities to which Guiard's model applies.)

Through surveying a wide variety of these asymmetric manual tasks, patterns emerged, leading Guiard to posit three principles governing the asymmetry of bimanual gestures (given in reference to a right-handed individual):

1. Motion of the right hand is typically relative to the position of the left hand, not the general environment.

2. Motion of the left hand is less frequent and of greater amplitude than that of

the right. (The right hand tends to move more rapidly and work at finer scales.)

3. The left hand's contribution to the current action starts earlier than that of the right.

Point 2 says that, rather than one hand being more skilled than the other, it is more a matter of one hand[1] being specialized to operate at larger spatial and temporal scales of motion (*macrometric*), and the other being specialized to work at smaller scales and finer resolution (*micrometric*). For "right-handed" individuals, it is the left hand that is macrometric, and the right hand that is micrometric; and, of course, for "left-handers", it is reversed. This represents more accurate terminology than the common P/NP (preferred/non-preferred) labelling and will be used throughout this document, except where referencing work in which the latter terms are used.

These principles are evident in any number of examples we may care to name: In sewing a button, hammering a nail, chopping vegetables or stirring a pot, the left hand clearly moves first, stabilizing and orienting the "material", and remains relatively still while the right hand performs its manipulations. However, the left hand need not remain unmoving to provide a point of reference: when one swings a golf club, for example, the left arm controls the swing and the left wrist provides the point of reference for the right hand's work in controlling the acceleration of the club, relative to the wrists, just prior to and through impact.

Guiard then draws a parallel between these principles and the action of a pair of motors connected in series. When two or more motors are connected in series, by rigid links, they form what is called a "kinematic chain". In this configuration, the motion created by the second motor in the series (the more *distal*, or furthest from the body or frame, of the two) is relative to the motion created by the first motor (the more *proximal*, or closest to the frame). If we equate the right hand (again, in a right-handed individual) with the more distal motor, and the left with the more proximal, we find that motors in series generally follow the same three principles defined for

[1] Buxton et al. [4] point out that although "so-called 'hand' movements of interest in HCI are actually extremely complex from the point of view of anatomy", "it is only at the level of assemblies of degrees-of-freedom that behaviourally meaningful *gestures* can take place" and ultimately, "the effectors that can perform gestures are the hands" (p. 11.1). Thus, it makes sense to simplify the discussion by using "hand" as a shorthand (no pun intended) for the entire assemblage of hand, wrist, forearm, elbow, upper arm, etc.

asymmetric bimanual activities. Thus, he concludes, we can use the kinematic chain as a model for this type of manual activity.

Thirty years on, this model is well supported by experimental evidence and has formed the basis for much of the subsequent work in two-handed computer interfaces. For the purposes of the present study, it is not actually necessary to validate this analogy; it is really only the three aforementioned principles that are applicable to user-interface design. However, the analogy provides a convenient shorthand by which to refer to the model: the *Kinematic Chain* (KC) Model.

2.2 Two-handed computer interfaces

Concurrent with Guiard's work, Buxton and Myers [3] found that, when given two input devices, one for each hand, and a task with two components that could be done in parallel (positioning and scaling a shape), nearly all the subjects (13 of 14) began doing the subtasks in parallel, nearly half of these (6 of 13) from the very beginning of the task, despite having been given instructions that were intended to bias them to do the subtasks serially. This suggests that perhaps we are indeed innately predisposed to use both of our hands when we can, and that it does not require extensive practice or training to take advantage of this kind of non-linear interface.

Further, even when the task did not lend itself to much parallelization, dividing the subtasks between the two hands was still found to improve overall task times by an average of 15% for experienced mouse users and 25% for novice mouse users. "In the one-handed approach, significant time is consumed in moving the pointer between the document's text and the navigational tools. In the two-handed version, the hands are always in home position for each of the two tasks, so no such time is consumed."[3, p. 325]

For any activity that involves using multiple tools, the total time to switch between

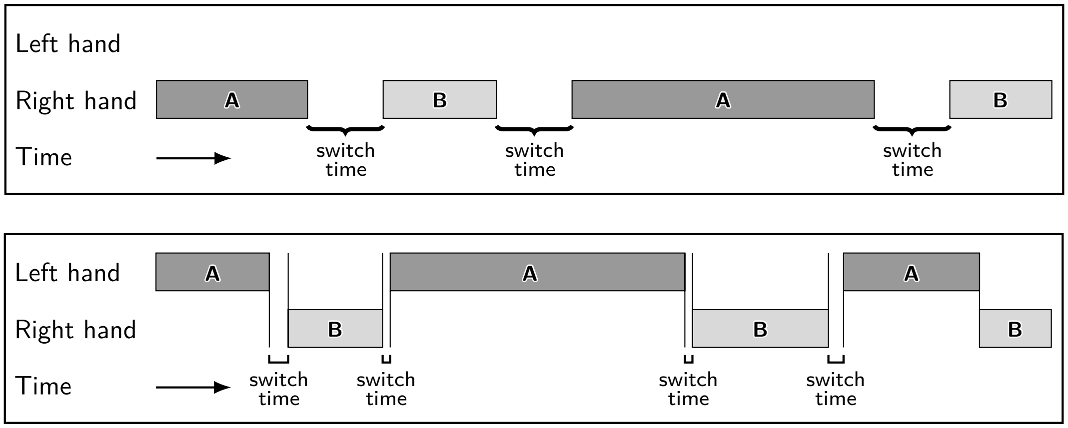

Figure 2.1: In one-handed operation (top), switching time includes cognitive switching time, visual redirection or reassimilation time, and device acquisition time. When the tasks can be divided between two hands (bottom), the switching time is reduced to the cognitive switching component. (Redrawn from [4])

tools consists of several subcomponents [4]:

- the "cognitive" switching time (to think about the new task)
- the time to redirect one's visual attention to the palette area of the screen
- the time to perform some motion to acquire the new tool
- the time to perform another motion to begin the manipulation with the tool

When one hand can be dedicated to each tool, the last three components fall away, leaving just the cognitive switching time. (Figure 2.1)

Dillon et al. [5] performed a study with a simple connect-the-dots task to try to isolate this switching time. They had users draw a series of short lines between pairs of circles, arranged in a fixed pattern. The colour of the lines alternated, and the task required the selection of a line-colour menu item between each drawing step. The control condition used lines of the same colour, so that no command step was required; the difference between the times was the time-cost of command selection.

They found that using two mice (one in each hand) was no faster than a single mouse, and that menu selection through a touch screen was nearly three times faster than either. This despite the menu being further away from the work area in the touch-input condition than for two of the mouse-input conditions, and thus resulting in a greater shift of visual attention away from the primary task. In addition, their experimental method of having a high ratio of command selections to drawing actions, with many repetitions, was found to be an effective means of obtaining reliable estimates of individual task times. Their methodology was followed in both of the next two studies, and adopted in the present study.

Kabbash et al. [12] modified the task slightly to present the dots one at a time and in constrained random arrangements. They compared single-handed mouse usage with three different bimanual input techniques (all using a trackball in the non-preferred hand). With one of these techniques—the Toolglass interface, which involves a movable tool palette that is placed over the target location and "clicked-through" [2] to apply—user performance was significantly better than the single-mouse technique with which the participants were familiar. However, with another of the two-handed techniques, performance was actually *worse* than with the one-handed technique (despite a reduction in total hand movement), providing a warning about failing to consider cognitive load or the differing abilities of the hands when designing bimanual interfaces.

Balakrishnan and Hinckley [1] point out that, with most input devices, there is no direct correspondence between the input and output spaces. When using a mouse, for example, "one's hand moves in a space that is separate from the display". And when using two separate devices, such as a pair of mice, not only are the hands disjoint from the display, they may also operate in spaces that are *disjoint from each other*. Such a configuration fails to take advantage of the body's innate sense of the positions of the two hands with respect to one another [9], and may actually work against it. In their study, the authors found that when both hands share the same kinaesthetic frame of reference, the user's reliance on visual feedback is reduced, allowing some activities—such as positioning a command palette—to be done without having to shift one's visual focus away from the primary task.

2.3 Touchscreen interaction

Wagner et al. [21] studied two-handed touch interaction with tablets, where the tablet is being held by the user's "non-preferred" hand. They compared holds where the tablet was held between the thumb and fingers, at the side or bottom, against holds where the tablet was supported on the forearm and held by fingers curled over the top or opposite edge. “Interaction zones” were introduced along the edges and extending from the bottom corners of the screen, where the fingers or thumb of the gripping hand could reach them, and different types of interactions (*taps*, *chords*, and *gestures*) were tried with the different holds.

Although they did find that performance often improved with the bimanual techniques, users found it difficult to perform gestures with the thumb or fingers of the grasping hand, and chords (which are applicable only to forearm-supported holds) were impossible for some to perform, due to limited reach of the fingers in some holds. Single-finger taps with the grasping hand *did*, however, outperform the unimanual form, and are an available technique with most tablet holds. It is recommended, however, that software support multiple placements of buttons, to allow users to choose and to change holds during use.

2.4 Modes, mode errors and kinaesthetic feedback

Mode errors [14, 16] are defined as instances in which a user performs an action that is appropriate for his or her assessment of the situation, but which is not appropriate for the *actual* situation. In computer software, this is typically because the application is in a different *mode* than what the user thinks it is (hence the name).

An example of this would be an attempt to add text to a document while the word processor is in a state where it only accepts commands. The text entered prior to realizing the error can set off the execution of one or more unintended operations, which could result in data loss (if the software does not have a forgiving “undo” mechanism) and, at the very least, the loss of time to recover and get into the intended mode.

Mode errors often occur when the user’s attention has strayed from the application, perhaps because of an external interruption or while pausing to work out a thought about the work to be done next. When returning to the application, one’s focus is often that next bit of work and it is easy to forget that one had left the software in the middle of some other multi-step action. For example, you might be in the middle of applying some styling to a block of text; you’ve highlighted the text, and then a colleague knocks on the door to ask a question. You turn, talk for a bit, and the conversation reminds of you of something you wanted to include in the text. You turn back to the keyboard and start typing—replacing all the text that was previously highlighted for styling. You curse, hit Undo, reposition the cursor, and start to type... and have now forgotten that perfect turn of phrase.

In certain conditions, mode errors can be catastrophic, damaging equipment or resulting in injuries or deaths [16, chpt. 5][18, chpt. 3]. But even when the consequences are less drastic, they can still be a source of frustration for users. Norman [15] suggests three ways to minimize mode errors: (1) providing adequate feedback on the system's current state; (2) making actions different in each mode so that they have no harmful effects in other modes; and (3) not having modes. Hardware limitations often get in the way of number 2, and number 3, while ideal, is often impractical. While not the solution to every usability problem, improved feedback (option 1) can go a long way to improving the usability of a system.

Sellen et al. [20] described five dimensions along which feedback can be characterized, and presented the results of experiments that compared kinaesthetic feedback (using a foot pedal) with visual feedback (changing the background colour of the screen from white to pink), and user-maintained feedback with system-maintained. In fact, the very example described above (switching between text entry and navigation modes of a text editor) was the task used in their experiments. They found that for feedback to be most effective, it should be *proactive* (rather than reactive), *sustained* (rather than transient), *demanding* (rather than avoidable), and *user-maintained* (rather than system-maintained), and that "[t]his kind of feedback is most naturally provided in the kinaesthetic domain".

When the traditional mode-switching keyboard commands were replaced by a foot pedal, both the frequency of mode errors and the task-completion times dropped dramatically. Critically, though, it was only when the foot pedal was used in a non-latching style (requiring the user to maintain the force on the pedal to remain in text-insertion mode) that it was found to be more effective. When operated as a latching toggle (switching modes each time it was pressed and released), the pedal was no better than using the keyboard for mode selection.

Their results suggest that the constant kinaesthetic feedback provided by the non-latching foot pedal is more salient than visual feedback. But why? For one, it is likely that kinaesthetic feedback is harder to ignore than visual feedback, and does not compete for the user's visual attention (which is already engaged in the primary task). Additionally, with the foot pedal, the feedback is delivered through the limb that was also effecting the mode change (as opposed to visual feedback in response to a keypress), providing a more direct communications channel. Distributing the subtasks among the limbs, rather than multiplexing the hands, may also reduce the cognitive load and context-switching time, and allow the subtasks to be overlapped to some degree.

On top of the faster operation and reduced error rates, it was found that users were able to resume the task more quickly after an interruption when using the non-latched foot pedal. Since relaxing the pressure on the pedal was all that was required to return to navigation mode, interruptions tended to leave the system in a known and easily identifiable state upon one's return. It also provided users with a very easy and reliable means to escape any mode and quickly get into a known state.

This same technique has also been shown to work well with touchscreens, where the surface provides the kinaesthetic feedback to the user's fingertips [23, 22]. Using the "non-dominant" (macrometric) hand to establish and maintain modes while the "dominant" (micrometric) hand does work within that context, as opposed to the use of standard persistent modes, provides sufficient feedback to alert the user to the continuance of the mode, and, as with the foot pedal, provides an easy way to escape the mode by simply lifting one's hand from the screen. These modes might be invoked by holding a finger or thumb on an onscreen button representing a tool [23], or through a held gesture [22], the mode being exited automatically when the touches are removed.

Furthermore, this particular arrangement (which follows the KC hierarchical model of motion, described earlier) has been shown to be a natural fit for touch interaction. When Frisch et al. [6] allowed users to come up with their own gestures for one-handed touch, two-handed touch and pen+touch interaction techniques for a series of diagram editing tasks, (on a large tabletop surface display), many spontaneously came up with two-handed gestures that involved placing the "off" hand on the table surface as a means to define the boundaries of a mode, while using the other hand (with or without a pen) to perform the manipulation.

These previous findings, combined with a return to the source of the KC model, have inspired the two-handed touchscreen interface proposed in this thesis, described next.

Chapter 3

A bimanual asymmetric touch interface

Today's "multi-touch" displays (which can distinguish multiple simultaneous touches), and the larger screens of tablets and tabletop "surface" computers, make it feasible to create a touch interface that easily supports the use of two hands at once. The question is: what is the best way to do this?

When one looks at applying the Kinematic Chain principles to two-handed computer interfaces, one needs to map input activity subtasks to the macrometric and micrometric scales of the hands. Many applications provide a collection of "tools" that may be applied to the "work"; typically one of these tools must first be selected, in order for it to be used. Tool changes generally happen with a much lower frequency than manipulations using the tool, and most certainly at a larger temporal scale than the manipulations (which can only happen once a tool is chosen). Thus it would seems that, temporally, the macrometric hand should select tools (modes of operation), while the micrometric hand applies the tool to the work.

In the spatial dimension, it is important to take into account the macrometric hand's lower resolution of motion. Commonly, on-screen buttons (or physical keys, where possible) are used to select tools or modes. These buttons should have large activation areas and require a minimum of attention to locate and differentiate between them. Through careful positioning and arrangement, it should be possible to operate the controls almost "by feel", even on a touchscreen, by using the edge of the device, for example, as physical a point of reference.

In both dimensions, the act of kinaesthetically "holding" a mode is analogous to the common stabilization role played by the macrometric hand in other manual activities. There would appear to be a natural mapping of real-world bimanual activities to this style of interface. Sellen et al. [20] found that the participants in their experiments expressed a "strong preference for the sustained foot pedal and consistent dislike of the latching foot pedal". "Latching" modes are required when multiplexing a single input device between the macrometric and micrometric levels of tasks, and may be favoured when a mode must be maintained for long periods of time (a power switch, for example), but for cases where modes are switched often, it is hypothesized that quasimodes will be a better fit.

The proposed bimanual interface (a simple example of which can be seen in Figure 4.2, as part of the discussion of the software prepared for the user study) presents a group of on-screen buttons for selecting the active application mode, but a selected mode remains active only as long as the activating touch remains in contact with the original button. This arrangement serves several purposes:

1. it keeps the macrometric hand still and positions it close to the work area, to provide a steady frame of spatial reference for the micrometric hand;

2. the pressing and releasing of the mode-selection button defines a temporal frame of reference for the micrometric hand's manipulations;

3. the pressing and *holding* of the mode-selection button provides the kinaesthetic feedback that reminds the user of the ongoing activation of the mode; and

4. it provides an easy way to escape the mode, simply by removing one's hands from the device.

For the user study described in the following chapter, we developed a custom iOS application (using Objective-C) that can track multiple independent gestures and replaces the standard controls with our own. The software presents a simple connect-the-dots task, similar to the ones used in the previous studies described in Chapter 2, but here for a touchscreen. It records the time taken to complete each step and each sequence, as well as a timestamp and position for all touches, for offline analysis (which was performed with the R statistical package).

Chapter 4

Study design

To test the effectiveness of the previously described quasimodal interface with a broad population, an experiment was designed that follows previous bimanual studies by Dillon et al. [5] and Kabbash et al. [12] (using a simple connect-the-dots task), but which uses a touchscreen tablet as the sole input device. The goal of this study was to compare user performance and satisfaction with a bimanual quasimodal input technique, using the standard unimanual latching-style touchscreen interface as the control condition.

Performance data captured included times to complete each step, the time spent on “drawing” (versus colour selection) and total times for each round. Short post-task interviews were used to guage user preference between the input techniques, and to collect ideas about how and where the bimanual technique might be best applied (if anywhere).

4.1 Task

The experimental task was based largely on the colourized connect-the-dots task described by Kabbash et al. [12], modified to use a single multi-touch touchscreen device and to use only touch input. Another difference was that instead of connecting the dots one-to-the-next, here, each pair was independent. This was done to minimize clutter on the small screen, which, it was feared, could lead to increased visual seeking times.

Figures 4.1 and 4.2 show the study task software in action. At the beginning of each trial, a filled circle, in one of three colours, appeared somewhere on the screen. The user was to first select the corresponding colour from a row of buttons along the side of the touchscreen (using the current interaction technique) and then draw a line from the starting dot to a goal dot that appeared after touching the first dot. The software ignored touches on the starting dot unless the correct colour had first been selected in the toolbar.

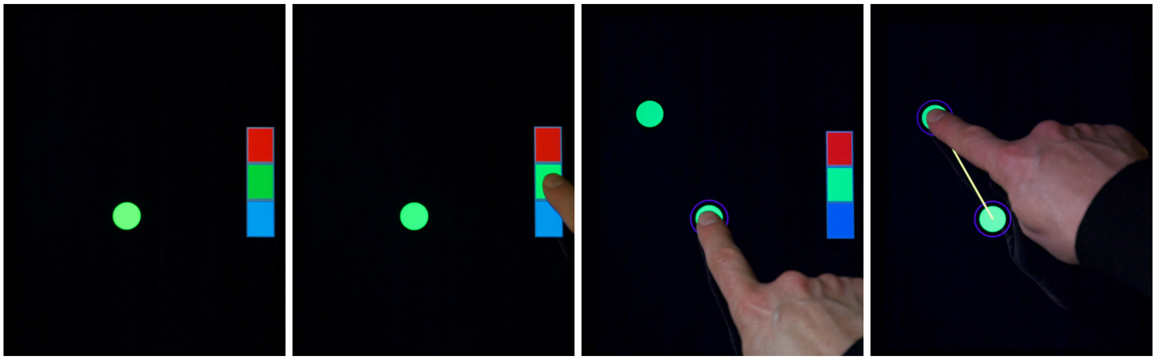

Figure 4.1: Unimanual modal operation (left-to-right): (a) A single dot appears, in one of three colours. (b) The user taps the corresponding colour in the toolbar to select a drawing colour. (c) The user then touches the starting dot to make the goal dot appear. (d) Dragging from the starting dot to the goal dot completes the step.

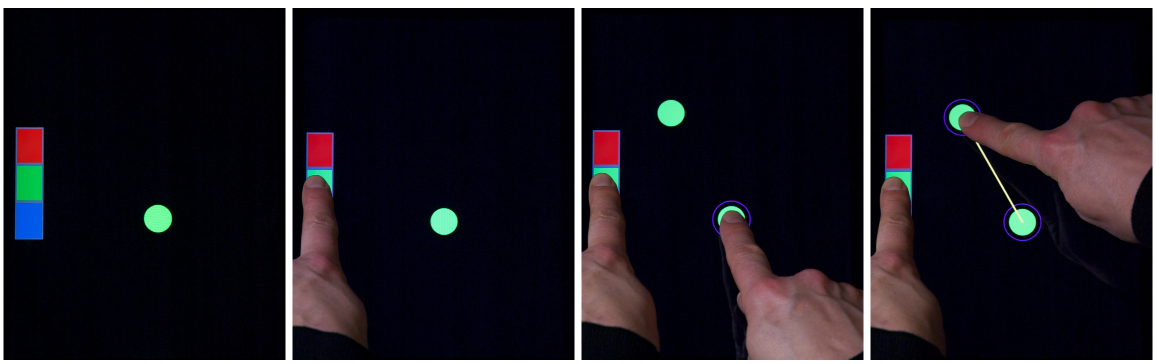

Figure 4.2: Bimanual quasimodal operation: The colour palette is always on the side of the macrometric hand and colours are selected by touching (and *holding* the touch) using the macrometric hand. Line drawing is done with the micrometric hand, while actively maintaining the “mode” with the macrometric hand.

After a connection had been successfully made, both dots would be removed and a new starting dot appeared, always in a different colour from the previous pair. The user repeats the colour selection step for the new dot’s colour, then draws a line from the new starting dot to the new goal dot, and so on until the end of the set.

Consecutive pairs of dots were always different colours, so as to maximize the amount of context switching between “command” selection (choosing a colour) and the drawing task. (One must alternate between the two subtasks.) This increases the proportion of time spent on the part of the task that differs between conditions (that is, the command selection task), which has been shown to be an effective means to obtain “efficient estimates of task times that are sensitive to the interface conditions and are statistically reliable” [5].

Each round consisted of a sequence of dot pairs of varied spacing, ranging from approximately 50 to 120 mm apart. The “dots” were each about 15 mm in diameter—slightly larger than the average fingertip, making them easy to target. Each sequence consisted of twenty pairs of dots, and participants performed ten sequences for each condition (plus two practice sequences for each). The sequences were pre-generated, from random positions, filtered for minimum and maximum separation. The same sequences were used for all participants, but presented in a different order to each. The order of sequences was the same for both of a participant’s two conditions, in order that the results be more comparable at the individual level. There were additionally two practice sequences, which were the same for all participants.

Although piloting showed that most participants reached their peak speeds after just a couple of trials, it was noted that often their speeds actually started to *drop* after six or seven trials, possibly due to fatigue. This seemed like a potentially interesting effect, so it was decided to keep the number of trials at ten per condition, in order to observe whether this was a common phenomenon.

4.2 Experimental conditions

All participants performed the same task using two different interaction techniques, in a within-subjects design. The ordering of the techniques between participants was alternated so that half (the odd-numbered participants) did the unimanual technique first and the other half (the even-numbered participants) did the bimanual technique first.

The two input techniques being compared (described with reference to a right-handed individual) were:

- *Latched unimanual*—the control technique. It represents the standard interface technique in almost all touchscreen tablet software today. A fixed-position palette containing a strip of buttons is positioned along the left or right edge of the screen. The current program “mode” is selected by tapping on one of buttons in the palette, which engages (*latches*) the mode until some other button is tapped. In this condition, users performed both mode selection and the primary task with the right hand.

- *Quasimodal bimanual*—modes are selected using one's left hand from a palette fixed to the side of the screen nearest that hand. The mode is engaged only so long as the user maintains a touch on the command button—hence, a "quasi-mode". (See Figure 4.2.) Actions performed within the work area (with the right hand) are interpreted within the context of the active mode, for example, dragging from one point to another to draw a line.

The bimanual technique was designed with Guiard's Kinetic Chain principles in mind [7], having both hands sharing a kinaesthetic frame of reference (the tablet's touchscreen) and with the macrometric (left) hand moving first in a command gesture that provides the context for work to be performed by the micrometric (right) hand. The two subtasks are well matched to the relative capabilities of the hands [12], command selection requiring coarser and less frequent movement than drawing.

For the bimanual technique, the colour bar appeared on the side of the screen corresponding to the hand that made command selection (the left for right-handers, and the right for lefties). For the unimanual technique, the bar was initially placed on this same side, however, after some of the early participants commented that they felt that having to reach across the screen was slowing them down, the position was switched to the other side for the second half of the participants, to see if it made a significant difference. (As we will see in Chapter 5, it did not.)

One of the previous studies [5] used a baseline task with no command selection steps (i.e., just drawing lines, all the same colour), interspersed with the conditions being studied, to attempt to isolate the time taken just for command selection; two others [1, 12] did not. The software written for the current study was instrumented to record the time spent on drawing so that this could be separated from the total task time. While this does not provide an exact measure of time spent on command selection (which would require seeing into the user's mind to determine precisely when the context switch takes place), it provides a means to extract an approximate measure of how the user's time was split between the two parts of the task, without requiring the subject to perform another whole set of sequences.

At the end of each sequence of dots, participants were shown their time for the set and their best time so far. They were instructed to try to complete the task quickly, while trying to minimize mistakes. For many, the presence of the timer turned it into a game, and some got quite competitive. While this may have helped improve times for some, it may also have resulted in slightly lower average times in some cases, due to a greater number of errors as a result of focusing more on speed than accuracy. Overall, however, it seemed to be an effective feature.

4.3 Study environment and apparatus

The user study sessions were conducted on an individual basis, in a quiet meeting room. Participants performed the tasks using our custom software running on a first-generation Apple iPad tablet computer, which has a 9.75″ (247 mm diagonal) screen and capacitive touchscreen overlay that can simultaneously detect independent touches from all ten fingers. The only other equipment required was an audio recorder, used to capture the interview part of the session, so the entire setup was easily portable.

Each session lasted about 35–45 minutes, consisting primarily of the participant exercise (approximately 10 minutes for each input technique), and a brief oral interview after the completion of the exercise (about 10–15 minutes). There was a brief paper questionnaire to complete at the end of each input technique, and the consent form and a background questionnaire to complete at the start of the session.

Participants were given the opportunity to take breaks at any point between trials (though no one required this) and between the two input technique blocks. Each of the techniques was first described and demonstrated by the researcher; the participant was then allowed two rounds of practice before beginning the recorded trials. Participants were instructed to position or hold the tablet as was comfortable, with most choosing to leave it on the table in front of them.

4.4 Data collection

The software recorded the times to complete each trial (one sequence of dots), and the time to complete each connection within a trial. The dot positions are also part of the data, to allow for the locations and the distances between dots to be taken into account during analysis.

Errors in colour selection and targeting were recorded by observation; however, with only one observer, it was impossible to do this with 100% accuracy. Instead, the goal here became simply to note patterns within and between participants, and to identify areas that might warrant further quantitative study.

Short questionnaires, consisting of 7-point Likert scale ranking questions, were completed after each of the conditions, and a 5–10 minute oral interview was conducted at the end of each session to gather each participant's qualitative impressions of the interfaces, and any suggestions for improvements and applications for the techniques. See Appendix A for the contents of the questionnaires and interview questions.

4.5 Participants

Recruitment took place through Dalhousie University mass email services and word-of-mouth. There were 17 participants in the study, 12 male and 5 female. (One of the original 18 did not show.) Three of the participants were "left-handed", in that they performed the micrometric part of the task with their left hand. As the study task required participants to be able to quickly identify colours, all were tested to ensure they could identify and distinguish between the colours used, prior to beginning the task.

Previous experience with touchscreens was not a requirement, however, all of the participants had some level of smartphone or tablet experience (perhaps due to self-selection, but likely also due to the nearly ubiquitous presence of these devices in our culture at this time), although three considered themselves quite novice users. The remainder were regular to heavy touchscreen users. None had any previous experience with two-handed computer interfaces, beyond keyboards and game controllers (where the hands play more symmetric roles, different from the asymmetric roles to be found in the current experiment).

Participant ages ranged from about 20 to 70 (participants were required only to select an age category, so the exact range is not known), though recruiting through the university inevitably drew a large proportion of participants (41%) who were

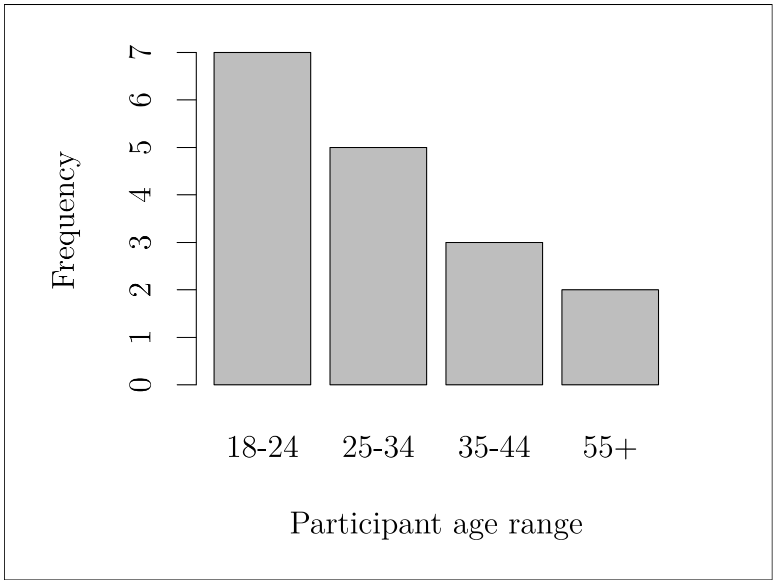

Figure 4.3: Participant age breakdown.

under age 25. (See Figure 4.3 for a full breakdown.)

4.6 Research hypotheses

Going into the study, it was expected that the following effects would be found in the experimental data:

H1. Once learned, the bimanual technique will be faster for command-selection, and faster overall, than the unimanual technique.

H2. The bimanual technique will be less mentally taxing (manifested as fewer errors in choosing the next action to perform, in choosing the correct colour, or in forgetting to choose a colour) than the unimanual.

H3. The bimanual technique will feel more natural (for the activity being used in the study) than the unimanual.

Chapter 5

Results

5.1 Performance

5.1.1 Task completion times

The first point of comparison is the overall task times. As described in Chapter 4, each participant in the experiment completed 10 sequences of 20 pairs of dots for each input condition (one-handed with modal command selection, and two-handed with quasimodal command selection).

Figure 5.1 shows a visual comparison of participants' overall times with the two experimental conditions. Each box represents the set of trial completion times for one participant in one of the two conditions, each participant's samples grouped together into pairs for easy comparison. The vertical bounds of the box represent the first and third quartiles of the samples in that group, the whiskers entending to the *most extreme* values of the sample group (differing from the usual extension of 1.5 times the interquartile range), save for the identified outliers,[1] which are indicated by circles. In two of these cases, the user started the timer before being ready, and in the other, the user made the same mistake several times in succession, causing the time to be much higher than for the other trials.

It is evident from this graph that most participants completed the experimental task notably faster in the two-handed/quasimodal condition than in the one-handed/modal condition. It also shows that, within each participant-condition grouping, the trial times generally don't vary much (as indicated by the short boxes for most of the groups), the variation slightly less within the two-handed condition groups.

Table 5.1 lists the mean[2] and standard deviation for the trial-completion times,

[1] Potential outliers were identified using modified Z-scores [17], relative to the samples in each group (participant-condition). That is, a sample was considered an outlier only if it was inconsistent with other samples belonging to the same indvidual, for that particular condition.

[2] Geometric means are often used for task times [19], however, as the comparisons here were only within participants, and as these times did not tend to have large variances, the difference between the geometric mean and standard mean was found to be insignificant (under 0.1%). It was thus decided to stick with plain means.

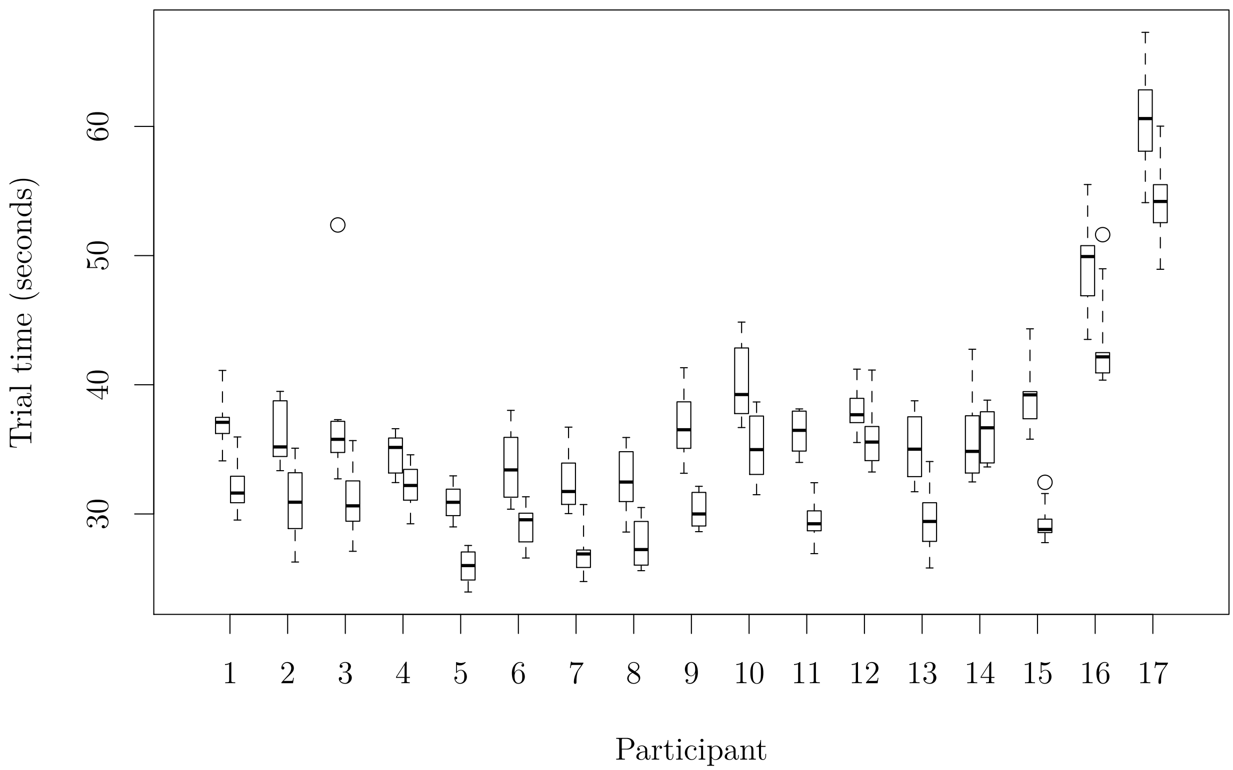

Figure 5.1: Trial times by participant and condition. For each participant, the box on the left is the one-handed condition, the box on the right is the two-handed condition. Box extents show the first and third quartiles for each group, and the whiskers extend to the full range for the group. Circles represent outlier trials (not included in group ranges).

by participant and input technique (after removal of the three outlier trials shown in Figure 5.1). The standard deviations scores confirm the low variances seen in the boxplot, above.

The "Difference" column lists, for each participant, the mean trial-time difference (in seconds), between conditions. It shows that, on average, **all but one of the participants completed the task more quickly using the two-handed technique**—a technique that *none* of the participants had ever used on a touch screen before. (And interestingly, the one participant who was faster with one hand still expressed a strong preference for the two-handed technique. See the discussion in section 5.3, Preferences, later in this chapter.)

The trouble with using the raw times for comparison is that participants who

Participant	One-handed M	One-handed SD	Two-handed M	Two-handed SD	Difference	Ratio	% change
1	37.2	2.2	32.2	2.0	-5.0	0.866	-13.4
2	36.2	2.3	30.9	2.7	-5.3	0.854	-14.6
3	35.7	1.6	31.1	2.9	-4.6	0.871	-12.9
4	34.6	1.5	32.1	1.7	-2.6	0.926	-7.4
5	31.0	1.3	25.9	1.2	-5.1	0.835	-16.5
6	33.7	2.6	29.1	1.6	-4.6	0.863	-13.7
7	32.3	2.2	27.1	1.8	-5.3	0.836	-16.4
8	32.7	2.3	27.7	1.8	-4.9	0.849	-15.1
9	36.8	2.4	30.2	1.3	-6.6	0.821	-17.9
10	40.3	3.0	35.2	2.6	-5.1	0.874	-12.6
11	36.3	1.6	29.4	1.4	-6.9	0.811	-18.9
12	38.0	1.8	35.7	2.3	-2.3	0.939	-6.1
13	35.1	2.5	29.6	2.3	-5.5	0.843	-15.7
14	35.8	3.1	36.3	1.9	0.5	1.015	1.5
15	38.9	2.4	29.3	1.2	-9.6	0.754	-24.6
16	49.6	3.5	42.5	2.6	-7.1	0.857	-14.3
17	60.8	3.9	54.1	2.9	-6.7	0.890	-11.0
Mean					-5.1	0.865	-13.5
Standard deviation					2.2	0.0572	5.7

Table 5.1: Mean trial completion times, in seconds, the difference between the means, and the ratio of two-handed time to one-handed. The rightmost column shows the percentage change between the one-handed and two-handed conditions' mean times (negative values indicating that the two-handed condition's time is faster).

completed the task more slowly than others tended to have larger absolute differences between the conditions than those who were faster, and these larger values have a unfairly greater influence on the mean and variance of the differences than those of the faster subjects. Ratios, on the other hand, provide a measure of variation that is less sensitive to between-subjects differences in absolute speed, and which is also independent of the number of repetitions of the task. A ratio can also be applied to other users and other activities to get an estimate of the expected performance level with the two-handed technique in other situations, making it a more useful statistic.

For these reasons, the ratio of mean times for the two conditions (the control condition in the denominator) was calculated for each participant (seen in the "Ratio" column of Table 5.1) and these were used for further analysis, instead of absolute times. The value is also presented as a *percentage change* (the difference between the condition mean times as a percentage of the control condition time; seen in the rightmost column) as a more intuitive measure of the rate of improvement (when negative) or performance decrease (when positive) with the two-handed technique, relative to the one-handed.

To test the statistical significance[3] of these results (that is, whether the differences observed in our sample are unlikely to have happened strictly as a result of sampling variance, making it reasonable to infer a similar difference in the populations from which these samples were drawn), a Wilcoxon signed-rank test[4] was performed on the ratio data ($M = 0.865$, $SD = 0.0572$). The null hypothesis being tested is that, for each individual, the mean time to complete the task is not affected by the choice of input technique, i.e., $\mathrm{H_0}$: $\mu_2 \div \mu_1 = 1$, $\mathrm{H_a}$: $\mu_2 \div \mu_1 \neq 1$.

The Wilcoxon test indicates that there *is* a significant difference between the two input conditions ($T^+ = 1$, $p < 0.001$), so we reject $\mathrm{H_0}$ in favour of $\mathrm{H_a}$.

Using the same nonparametric test, the 95% confidence interval for the *median* percentage change is calculated as $(-16.1, -11.0)$, that is, we can expect an average improvement of about 11% to 16% with the two-handed quasimodal technique used in this study, over the standard one-handed touch input style currently in use. And that is without any previous experience with the technique; in real use, performance with the new technique will likely improve further with practice.

5.1.2 Command selection times

A shortcoming of using trial times for comparison is that they include the time spent "drawing", i.e., connecting the dots, as well as making the colour selection. The software, however, also recorded the time from when the user touched the first dot of each pair to when the connection was completed. Subtracting drawing time (from when the starting dot is touched until the connection is successfully completed) from

[3] All statistical significance tests in this chapter are two-tailed and use $\alpha = .05$ as the reference point for significance.

[4] The Wilcoxon signed-rank test is a non-parameteric equivalent of the Student t-test for paired samples, providing more accurate results when the distribution of the sample data is non-normal. The T^+ test statistic is described in Hollander et al. [10, p. 40].

the overall step time gives an approximation of command selection time.[5]

Unfortunately, during the first day of user sessions, the software failed to record step connection times, so there is no data from participants 1–6 available for use in this part of the analysis. However, the means of the trial time ratios of the two groups (those without step data and those with) are almost identical (0.8690 and 0.8626, respectively), and the spread of the trial times of the samples *not* being used ($SD = 0.0304$) is less than for those being used ($SD = 0.0690$) so our analysis should, at worst, be overly conservative in identifying significant differences. And as we were alternating the order of conditions for each participant, there were an equal number of each ordering dropped, leaving the counterbalancing of the order variable intact in the following.

Some further cleanup was also required to prepare this data for analysis. The first step of each trial was removed from the data set, as the command-selection time tended to be significantly inflated relative to later steps, probably as a result of participants being less ready when the first dot appeared than subsequent ones in the sequence. This still left an unusually high proportion of samples being flagged as potential outliers[6]—approximately 8% of the 4180 samples. The consistency of the "normal" times within each individual's set of samples (visible in the short boxes in the boxplots) suggests that these higher times (for, indeed, all of the flagged samples were *higher* than normal) represent instances of a user error that required an adjustment or a repetition of the step in order to successfully complete it. Although we were not able to obtain accurate error counts from observation, this percentage is consistent with what was observed. We will thus treat these values as indicative of user errors and examine them separately from the main observations.

Figure 5.2 shows that approximately 40% of the time is spent on dot connection, and that the times for this subactivity are approximately the same between conditions. This means that the difference in the command selection portion is actually greater than identified in the analysis of the overall trial times.

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[5]In truth, this slightly overstates the command selection time over a true no-command condition, as Dillon et al. [5] employed, as this time also includes the observation and planning time at the start of each step. However, this part of the task is likely to be pretty similar for both conditions, so its inclusion should only result in an *understatement* of the true difference.

[6]Potential outliers in the step data were detected using the same criteria as for the trial times.

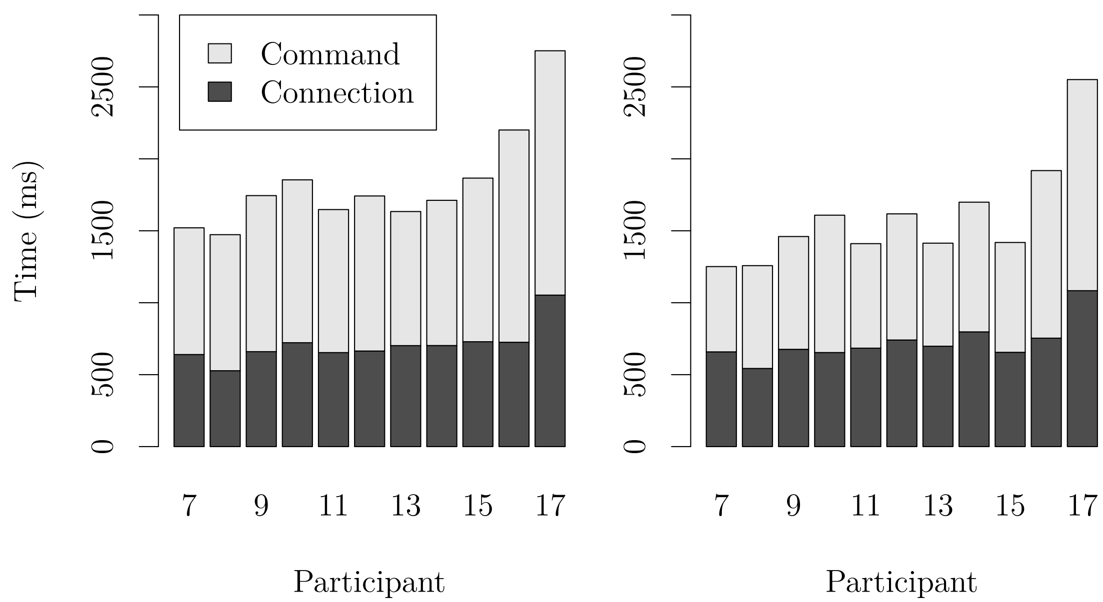

Figure 5.2: Breakdown of step subactivities: Mean times (in milliseconds), by participant. One-handed condition on left; two-handed on right.

Table 5.2, and Figures 5.3 and 5.4 highlight this further. For the majority of participants, the time to perform the dot-connection part of the task was not significantly different between the two conditions. There are two exceptions: two participants were about 15% slower on this connection activity in the two-handed condition. In both of these cases, the two-handed condition was performed first, so one might at first suppose that perhaps the subjects simply got faster at the task as they got more practice (an order effect). However, their per-trial mean times, listed in Table 5.3, do not support this. There is a large jump between the last trial of the two-handed condition and the first trial of the one-handed condition, and both actually start to *slow down* about halfway through the second set of trials (one specifically mentioned getting fatigued after the seventh trial of the second condition). Additionally, from the session notes, it does not appear that there were a greater number of errors observed in either condition for either of these participants.

It becomes evident, however, that the times in each case tend to converge in the later trials for each condition, suggesting perhaps that these participants just needed a little longer to adjust to the two-handed technique, and that, while they initially worked quickly with the familiar one-handed technique, they were unable to keep that

Participant	Command	Connection
7	-31.4	4.6
8	-22.5	3.0
9	-27.2	3.4
10	-14.5	-7.5
11	-25.8	7.0
12	-17.5	14.6
13	-21.6	0.8
14	-9.6	15.2
15	-32.3	-8.9
16	-19.9	3.9
17	-12.1	4.3
Mean	-21.3	3.7
Standard deviation	7.5	7.5
95% confidence interval	(-26.9,-16.0)	(-2.2,9.3)

Table 5.2: Mean percentage change between conditions for each subactivity, by participant.

	Participant 12		Participant 14	
Trial	Two-handed	One-handed	Two-handed	One-handed
1	823	612	928	635
2	780	614	810	698
3	829	609	814	689
4	737	612	734	664
5	755	688	819	753
6	697	688	799	735
7	632	621	824	728
8	777	742	754	638
9	714	758	735	745
10	709	686	748	741

Table 5.3: Unusual dot-connection subactivity times (in milliseconds).

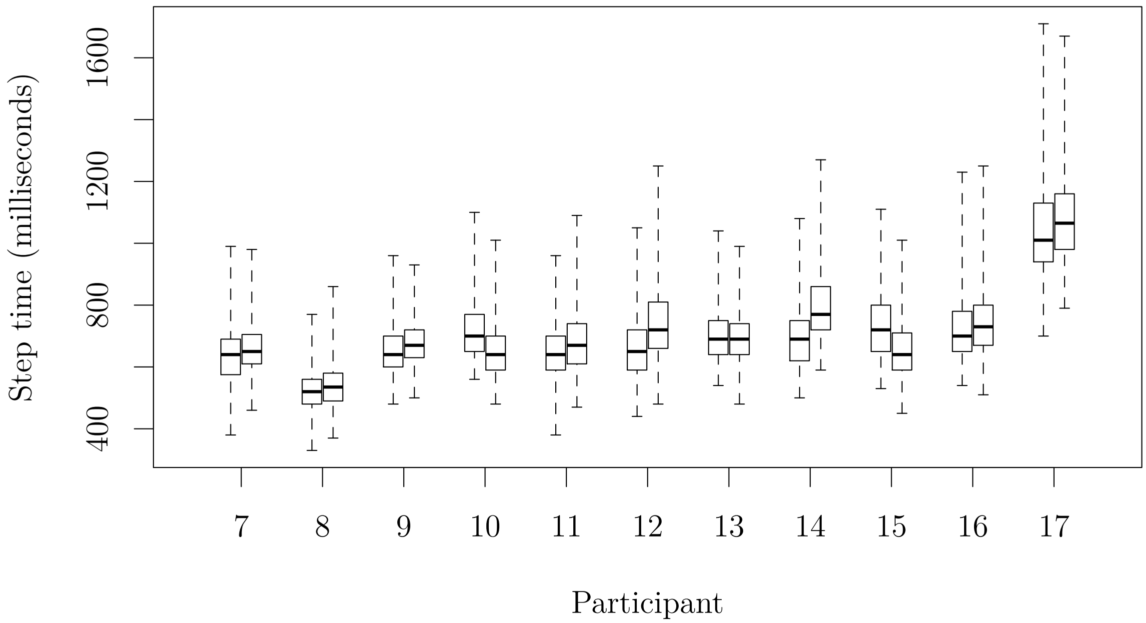

Figure 5.3: Dot-connection times by participant and condition. For each participant, the box on the left is the one-handed condition, the box on the right is the two-handed condition. (Outliers not shown.)

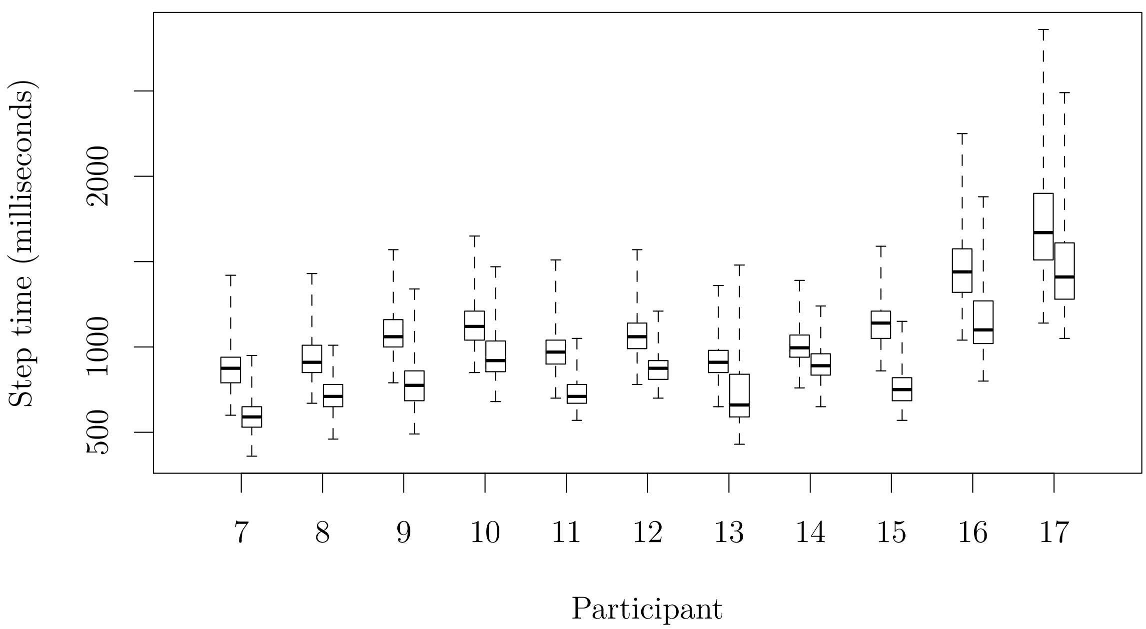

Figure 5.4: Command-selection times by participant and condition. (Outliers not shown.)

pace for very long and settled into a working speed that was similar to their speed with the other technique.

Returning to Table 5.2, and to Figure 5.4, with the command selection part of the task isolated, we can see that *everybody* was, on average, faster with the two-handed technique for command selection. And we can revise the earlier claim and say that now we can be 95% confident that the two-handed quasimodal technique will produce an average improvement of 16% to 27% over the standard one-handed touch input style for command selection. (The confidence interval is wider here than the earlier result because of the reduced sample size, as a result of the missing data for 6 participants.)

5.1.3 Errors

As mentioned above, precise information regarding numbers of user errors was not successfully collected. "Live" coding of errors during the session was attempted, but with only a single observer, and the rapid nature of the task, it was simply not possible to accurately observe and code all mistakes in real time. (Video recording would have made post-session analysis possible, but this issue was not foreseen during planning, so video recording was not included in the original study design.)

While analyzing the time data captured by the software, however, it was noted that the proportion of step samples that were flagged as potential outliers was fairly consistent with the frequency of mistakes observed during the sessions (see the Ratio column of Table 5.4); and that most of these flagged times were so far out of line with the "normal" times observed for each user that it seems quite likely that these samples represent instances where the user had to make an adjustment or repeat the action in order to complete the step.

If we treat these outliers as indications of user errors, we can perform some quantitative analysis on them. For example, Table 5.5 shows the breakdown of errors by

	One-handed	Two-handed	Ratio
Errors observed	135	103	1.31
Outlier steps	195	156	1.25

Table 5.4: Comparison of user error detection schemes.

Participant	Command 1H	Command 2H	Command Diff.	Connection 1H	Connection 2H	Connection Diff.	Total 1H	Total 2H	Total Diff.
7	8	13	-5	6	7	-1	14	20	-6
8	7	4	3	16	18	-2	23	22	1
9	8	2	6	8	5	3	16	7	9
10	7	3	4	10	11	-1	17	14	3
11	12	3	9	15	5	10	27	8	19
12	16	16	0	10	10	0	26	26	0
13	8	1	7	13	9	4	21	10	11
14	2	6	-4	6	8	-2	8	14	-6
15	7	6	1	1	1	0	8	7	1
16	3	7	-4	13	16	-3	16	23	-7
17	4	0	4	20	12	8	24	12	12
Sum	82	61	21	118	102	16	200	163	37

Table 5.5: Error counts, by sub-task and condition.

activity and condition, and shows that fewer errors were made in the two-handed condition (25.6% fewer in the command-selection part of the task, and 13.6% in the dot-connection part). Figure 5.5 shows the same graphically.

To see whether this difference is significant, we test a null hypothesis that the mean error rate for command selection is not affected by the choice of input technique. $\mathrm{H_0}$: $\mu_1 - \mu_2 = 0$. $\mathrm{H_a}$: $\mu_1 - \mu_2 \neq 0$.

Again using a Wilcoxon rank-sum test on the paired error counts, we find that, in this case, we do not have sufficient evidence to reject $\mathrm{H_0}$ ($M = -1.9$, $SD = 4.74$, $T^+ = 16$, $p = 0.26$). So, although our participants did, on average, make somewhat fewer errors when using two hands, this may just be sampling variance at work. It is also possible that the reduction in sample size for the step data (due to the data recording failure) was a factor, and that, with a larger test sample, the difference might turn out to be significant.

With respect to the dot-connection part of the task, we assess the same null and alternative hypotheses, in the same way, and get the same outcome as above: the difference is not statistically significant ($M = -1.5$, $SD = 4.3$, $T^+ = 15.5$, $p = 0.44$).

In summary, given that we do not know for sure how strong the correlation between these outliers and actual user errors is, it would not be wise to put too much faith in these results as of yet. However, the coding of errors during the sessions, while

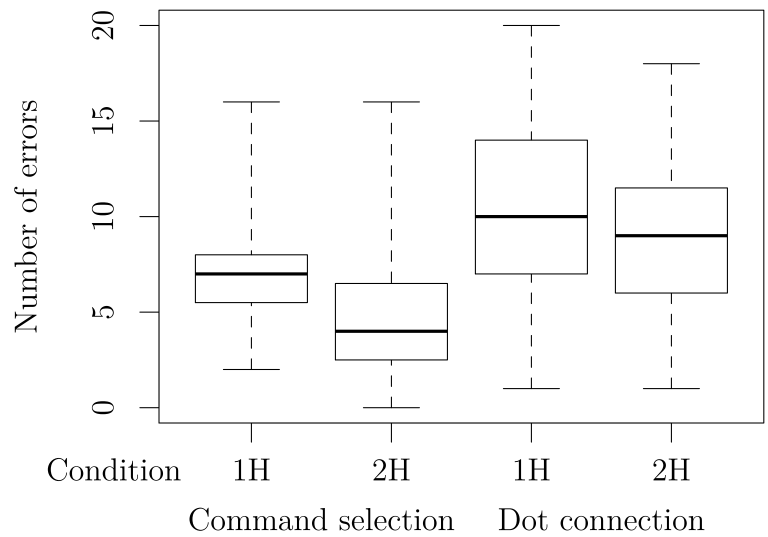

Figure 5.5: Error counts, by sub-task and condition.

incomplete, also showed that fewer errors were made in the two-handed condition. While preliminary, the results suggest that further study is warranted to determine the strength of the correlation between input technique and error rates, if any.

5.1.4 External factors

Breaking the results down by demographic groups (Table 5.6), we do not find any significant differences[7] in the task time ratios between the two conditions as a result of differences in age, gender, handedness, or even technical experience levels. (Because our recruitment drew a large proportion of technically savvy people, most of the participants fell into the top two categories for "technical level" and "touch experience", so we collapsed the rest into a single "novice" category, and processed each of these factors with just three categories.)

This is all pretty much as expected, although it is interesting that we do *not* see any significant difference in the ratios for novices and experienced users. Tables 5.7(a) and 5.7(b) show just how similar their results are, although the experts had greater variability in their level of difference. Although our sample size is too small to allow

[7] Both one-way ANOVA and Kruskal-Wallis tests were performed on the sample groups, the latter being more conservative, as it has no normality assumption. The test results were the same for all variables, and ANOVA is generally considered to fairly insensitive to minor violations of the normality assumption, and less sensitive to differences in variation between groups [13, p. 158], so only the ANOVA results are reported here.

Variable	df	F	p
Age	3,13	0.254	0.86
Gender	1,15	0.019	0.89
Hand	1,15	0.000	0.98
Computer experience	2,14	0.497	0.62
Touch experience	2,14	0.209	0.81

Table 5.6: Effects of sampling factors on ratio of bimanual-to-unimanual mean trial times.

Comput Exp	N	Mean	SD
Novice	4	0.881	0.045
Experienced	6	0.846	0.057
Expert	7	0.872	0.066

(a) By technical experience

Touch Exp	N	Mean	SD
Novice	3	0.870	0.018
Experienced	3	0.844	0.009
Expert	11	0.869	0.071

(b) By touchscreen experience

Table 5.7: Summaries of the bimanual-to-unimanual ratio of mean trial times, by participant experience levels.

us to conclude that there is no population-level difference, this might be something to look at more closely with a study that includes more novice users. However, this preliminarily suggests that two-handed interaction is not something that only expert users can master, and that even an expert user will hit a "wall" with the one-handed technique that limits his or her task performance when required to use such an interface.

5.1.5 Presentation variables

Order of presentation

On the other hand, the order in which the conditions were presented (which was balanced) *did* have a significant effect ($W = 13$, $p = 0.027$). Although both groups performed better with the two-handed condition, those who saw it first were on average only 10% faster at the overall task (17% faster at command selection), while those who saw this condition second were an average of 16% faster on the overall task (and 25% faster at command selection). The presence of a minor learning effect is not really unexpected, and is, of course, the reason for counterbalancing the order of presentation in the first place.

Palette Side	N	Mean	SD
Active hand	10	1.159	0.091
Opposite	7	1.164	0.047

Table 5.8: Effect of palette position on unimanual-to-binmanual ratio of trial times.

Unimanual palette side

Initially, we had the study software place the palette on the same side of the screen in both conditions (on the left-hand side for "right-handers", and on the right for "left-handers"), in the belief that keeping this consistent across conditions would provide a fairer comparison of the techniques. However, during the early sessions, several people mentioned that they felt that reaching across the screen was slowing them down.

The software was then changed to present the palette on the opposite side for one-handed use for the remainder of participants. Although an error in presentation in the last session caused this variable to not be properly counterbalanced, the two groups are still close enough in size for an effective comparison of the samples.

Table 5.8 presents a summary comparison of the unimanual-to-bimanual ratio of mean trial times for the two palette placements. There is no significant difference between the groups ($W = 36$, $p = 0.96$), and performance was, in fact, less consistent (more variable) with the palette in the "preferred" position (on the same side as the unimanual hand).

It would therefore appear that, contrary to some participants' beliefs, there was no real penalty for those who performed the experiment having to reach across the screen for the palette, versus those who had the palette on the near side, and we can safely ignore this variable in analyzing the task time data.

5.2 Observations

The software used for the study was not capable of detecting which hand or fingers the user is using, nor could it see *why* certain steps took longer or determine the reasons for longer gaps between steps. It was possible to capture some of this information through observation, however, as there was only one observer present, and video recording was not used, this could not be comprehensive. There were, however, certain patterns that emerged that seem to be of interest and which may warrant further study.

There was one particular pattern that stood out, observed repeatedly but *only in the unimanual case*: after completing a connection, and having seen the colour of the next dot pair, subjects would often have a moment of apparent indecision, the hand being used for interaction moving initially towards the starting dot, before correcting and heading to the colour bar. There would sometimes be a short back-and-forth motion between the two targets before settling on a direction. Or a pause in the movement, even when it was in the right direction, as if rethinking the move.

When asked about this in the exit interviews, many of the users were not even really aware of doing these things, while others reported forgetting one's place in the sequence, or having an internal "battle" between muscle memory (wanting to follow its rhythm and reach for the color bar) and one's "locus of attention" [18, p. 17] being on the next dot. The frequency with which this slip occurred was probably heightened by the simple and repetitive nature of the task, and by the presence of the timer, leading to users treating it as a game and trying to push themselves to go faster.

Nonetheless, this pattern is consistent with observations of users of modal software, in general [16, 18, 20] (and with the author's personal experience with such software). What seems notable is that, after the practice sequences, this type of slip was *very rarely* observed in the two-handed condition (on the order of ten times over thousands of trials), and order-of-operation slips (starting to draw a line before selecting the matching dot colour) were much less frequent in the two-handed condition as well.

Another type of error noted primarily in the one-handed condition was the use of the wrong gesture for the current task; that is, tapping on a dot, or dragging from the colour bar. This was noted at least once for nearly every participant in the one-handed condition, but only once for the two-handed. So, even though the gestures were alternated in both conditions, it seems that the assigning of a different gesture to each hand is much easier for our motor systems to cope with than having one hand switch between both.

Other types of errors included selecting the wrong colour, and mistargeting the colour buttons or the dots. These were common in both conditions, though mistargeting of the colour buttons was more common in the one-handed condition, which is not really surprising, given the longer distances that the selecting hand had to travel in that condition. On a related note, it was observed (as expected) that, after a few sequences, some users were able to make colour selections without really looking at the colour, using either their peripheral vision or just muscle memory.

The most common (and most frustrating) error was that of lifting the "drawing" finger when not over the target dot, often as a result of making more of a flicking motion, rather than dragging all the way to the target. This was approximately equally common in both conditions. Several participants wished aloud that the software was more forgiving about making the connection, and while the study software did allow for about a finger-width's "slop" on all sides of targets, it's probably true that a real software application might be designed to be more accommodating than this. Limiting the study software's targeting tolerance was a design choice, intended to prevent participants from being overly casual with their actions, but other changes to the software, such as showing both dots up front, might have helped to mitigate this issue.

5.3 Preference

For each of the experimental conditions (one-handed and two-handed), upon completing the full set of trials for that condition, participants were asked to complete a brief, six-item questionnaire (see Appendix A), in order to assess their feelings about the input technique they had just used. Participants were asked to rate their level of agreement (on a seven-point Likert scale, where 1 indicates strong disagreement, 7 indicates strong agreement, and 4 represents neutrality), with each of the questions in Table 5.9.

The mean[8] scores for all questions are on the high end of the scale for both conditions, with a small but consistent preference expressed for the two-handed technique. And on all but one of the questions (if we count that $p = 0.051$ on question 1 as

[8]According to Sauro and Lewis [19, p. 246], mean score differences more closely correlate with significance levels than median score differences for discrete multipoint scale data. For example, in some cases here, the median scores for the two conditions were the same yet the Wilcoxon signed-rank test and Student t-test both report a significant difference between the two samples.

Question	One-handed Mean	SD	Two-handed Mean	SD	p
I found this input technique easy to use.	5.6	0.9	6.2	0.81	0.051
I learned this input technique quickly.	6.0	1.4	6.5	1.23	0.031
I was able to get the task done quickly using this technique.	5.4	1.1	6.1	1.05	< 0.001
I didn't have to think very much about what to do with my hands, so I could focus on the task itself.	4.9	1.4	5.3	1.10	0.25
I did not feel any hand/arm fatigue or discomfort while using this technique.	4.9	1.6	5.9	1.20	0.025
I enjoyed using this technique.	5.2	1.6	6.2	0.95	0.029

Table 5.9: Means and standard deviations of post-condition ratings of each input technique, on a scale of 1–7. p is obtained using Wilcoxon signed-rank test on paired samples.

close enough), the differences are statistically significant. Particularly strong was the preference for the two-handed technique on question 3 ("I was able to get the task done quickly"); every participant rated the two-handed technique as high or higher than the one-handed technique on this particular point.

Additionally, 11 of 12 participants who expressed a preference scored the two-handed technique as less fatiguing than the one-handed. Even within those who performed the two-handed technique second, 4 of 9 scored the two-handed technique as less fatiguing (and none who scored the one-handed technique less fatiguing when it was done second).

The one point on which the techniques were relatively close (where the two-handed technique was preferred by only 64% of those who expressed a preference, and 41% of all) was with respect to "having to think about what to do with my hands". In the exit interviews (discussed next), several people mentioned that they felt they were having to think more about their actions in the two-handed condition; however, the performance numbers certainly do not really bear that out. Observation also told a different story: participants were far more likely to demonstrate hesitancy or confusion about the next step when using the one-handed technique than the two-handed one. It is harder to come up with an explanation for this, but it may just be that people were more aware during the unfamiliar condition, and thus felt the

Question	One-handed N	One-handed %	Two-handed N	Two-handed %	p
Which did you like the best?	3	0.18	14	0.82	0.013
Which felt the fastest?	2	0.12	15	0.88	0.0023
Which felt most natural?	4	0.25	12	0.75	0.077

Table 5.10: The numbers and proportions of participants who expressed a preference for one of the two input techniques, for the given questions. p is obtained using an exact binomial test on the N values.

passage of time more acutely, distorting their impressions.

Following the completion of the second set of trials, and its post-condition questionnaire, the final part of the session included a 10–15 minute exit interview. Here, participants were asked to choose which one of the two techniques they preferred, which felt the fastest, and which felt most natural, along with some open questions about how to improve the interfaces and where they might be best applied. (The interview worksheet also appears in Appendix A.) The latter part was more conversational, and we tried to dig into the reasons for the preferences expressed, while also providing an opportunity for general comments and questions from participants.

As shown in Table 5.10, over 80% of participants preferred the two-handed technique for the task, and nearly 90% said that the two-handed technique *felt* faster to use (including the one person who was actually slightly faster with one hand). In fact, one of the two who selected the one-handed technique as faster was quite surprised to learn that she had actually performed a good deal more quickly with the two-handed interface!

For the 25% who found the one-handed technique more "natural", the reason given was usually one of familiarity: they were used to the standard interface. This is certainly an effect that cannot be ignored—it is always a hurdle to break the grip of orthodoxy when introducing a new interface. On the other hand, our other evidence strongly suggests that users learn the new technique very quickly and most do come to prefer it in a very short time, so this may be a less difficult transition than others.

5.4 Summary

The overall preference for the two-handed technique is pretty clear—perhaps even stronger than anticipated. Performance was clearly better with the bimanual interface: 94% of participants completed the task in less time in the bimanual condition. Also, people generally found this technique less fatiguing and made fewer slips in this mode. But it is the strong preference for the two-handed interface and the speed with which people took to the technique that were the biggest surprises for us.

Notwithstanding the concerns raised about the applicability of the technique in mobile contexts, participants were overwhelming positive in their reactions to the new interface presented here, and several expressed the hope that something similar would become available in real products in the near future.

Chapter 6

Conclusion

6.1 Discussion of results

6.1.1 Performance

The experimental results presented in the previous chapter suggest that there are real efficiencies to be had with two-handed touch input, when it is designed in a way that is consistent with how our motor system works naturally.

Returning to the first of the research hypotheses that were stated in section 4.6:

> H1. Once learned, the bimanual technique will be faster for command-selection, and faster overall, than the unimanual technique.

We saw a mean 21.3% reduction in command-selection time with the bimanual interface, and we feel this is still on the conservative side (due to shortcomings in the study design, discussed in sections 5.1.2 and 6.3.3). The 95% confidence interval $(-26.9, -16.0)$ excludes 0, so there is very strong evidence that the results are indicative of the general population.

Similar but smaller differences were found on the overall task times ($M = 13.5\%$, $CI = (-16.1, -11.0)$), which is as expected, given that this includes the dot-connection times, which were very similar between two conditions (3.7% *slower*, on average, when using two hands).

Both of these results are in agreement with H1.

6.1.2 Reduction of user errors

The second of our research hypotheses stated:

> H2. The bimanual technique will be less mentally taxing (manifested as fewer errors in choosing the next action to perform, in choosing the correct colour, or in forgetting to choose a colour) than the unimanual.

Obviously, when planning the study, we had expected to be able to capture data on user errors, however, the reality was that the task steps happened so quickly, it was challenging for a single observer to both record and not miss any events. Looking back at each of the coding sheets, the numbers of errors were consistently lower in the bimanual condition for every participant save for one, however, we do not believe the actual numbers are accurate enough to use for analysis.

Generally speaking, it was far more common to observe hesitation between the colour-selection and dot-connection subtasks in the one-handed condition than in the two-handed. This is not surprising, as the one-handed style requires the user to switch actions between tapping and dragging on the same hand, which seems to require a greater amount of mental "context switching" than does having each hand doing only one of the two gestures. It was also more common in this condition to see users move from completing one connection to try starting the next, forgetting to perform the colour selection step. And we observed that participants generally took longer to resume the task after making an error—there was more fumbling around trying to remember where they were, and it took a bit longer for them to re-establish their rhythms. These observations are consistent with those reported by Sellen et al. [20] in their examination of actively-maintained kinaesthetic feedback that was described in section 2.4.

An attempt was made to generate some usable data out of the step times recorded by the study software (described in section 5.1.3), on the premise that abnormally long times in either the command-selection or dot-connection part of each trial step likely correspond to a user slip. (The study task is very repetitive and we observed that most participants fell into a rhythm when performing the task, their trial times hardly varying within each condition. Thus, any large deviations in the step times would be unusual and easy to identify in the data.)

Based on this data, we *did* see a reduction in the number of errors in the bimanual condition, however, the difference was not large enough to be statistically significant with the size of the sample we had. (Only 11 of the 17 participants' data was usable for this comparison, which may have been a factor.) So while our observations are in agreement with H2, we cannot use these results to infer anything about the population from which the sample is drawn. Nonetheless, the result is interesting and merits further study.

6.1.3 Preference

We come to the last of our study hypotheses, which said that:

> H3. The bimanual technique will feel more natural (for the activity being used in the study) than the unimanual.

In the exit interviews, 75% of participants indicated that the bimanual technique felt more natural than the unimanual. Considering that most of the participants had been using something similar to the study's unimanual interface for several years, and that this was the first time any of them had seen anything like the study's bimanual interface, this is a very strong result. Although it fell just shy of statistical significance at the study's α level, it is still noteworthy.

Comments indicated that those who preferred the two-handed technique found it less mentally taxing to have each hand dedicated to one task and one style of gesture, rather than having to flip back and forth between tapping and dragging. (Not surprisingly, it was at these points where the single hand changes roles that most slips were observed.) Many noted the similarity to day-to-day manual activities, where, as noted in Chapter 2, the involvement of both hands in a coordinated fashion is the rule rather than the exception.

Common reasons given for preferring the unimanual interface were familiarity (this style being nearly ubiquitous in current software) and wanting to be able to hold the device while using it. A few people felt that using two hands seemed harder or more complex, yet these same people did not appear to have any difficulty while performing the task, and all completed the task faster with the bimanual interface. Again, it seems likely that the unfamiliarity bothered some people, but the evidence indicates that learning the technique is quite easily done, and that new users would not suffer any performance penalty as a result of switching to the new interface.

6.1.4 Other observations

A few participants mentioned that, after some practice, they were able to perform colour selection without really looking at the toolbar. The left hand would at least partially rest on the edge of the tablet, and all the selection buttons were within a stretching reach of a finger, so it was possible to pick a target by “feel”. Some described it as using their peripheral vision to pick a colour. In either case, the small number of large, fixed targets successfully allowed users to perform the mode selection aspect of the task with minimal attention and distraction from the primary task.

6.1.5 Reflections on study task

Although simple and repetitive, the study task was effective at highlighting the differences between the interface styles. The performance difference (as a ratio of the times in the two conditions) was remarkably consistent across study subjects. The number of trials was sufficient for most participants to reach a plateau in performance well before the end of the session, and also enough to observe a general decline in performance in the unimanual condition, as people started to experience a bit of fatigue. And despite the repetition, participants generally found the task fun and (to our surprise) fairly engaging.

Starting with a new pair of dots each time meant that the user needed to spend approximately the same amount of time finding the new starting line position after each step, which equalized the two techniques to some extent. In practice, though, one of the advantages of the bimanual technique would be that it allows the user to spend less time re-acquiring their locus of attention, so the bimanual technique might have fared even better had a more realistic task been used.

6.2 Implications for design

A 20% to 25% reduction in command-selection time looks good on paper, but, of course, we do not spend all of our time selecting commands. The practical impact of switching to this style of interface will depend a great deal on the particular application. Software that makes heavy use of tools or short-lived modes, such as in drawing, photo editing, visual programming or some games, could see improvements that are not far off those seen in this study. Other software that has fewer mode switches may not see any noticeable difference in speed, and users may not like having to hold a button down for longer than a few seconds at a time.

There is also the matter of environment: Several participants raised concerns about trying to use something like this on the move—on their phones, for example. And tablets are often held in one hand (usually the macrometric hand) when used, which limits the range of the fingers on that hand. However, Wagner et al. [21] have already started to explore the use of touch zones placed along the edges of the screen, and for some applications, a small set of buttons arranged around one corner for the thumb, or along the opposite side for a forearm-supported grip, might work well.

The ideal environment for the two-handed technique presented here is likely the larger table-top and wall-mounted displays, where the user has both hands free for manipulating the interface. Evidence gathered so far suggests that tasks will feel most natural if the roles of the hands are assigned in such a way that the macrometric ("non-preferred") hand sets context (for example, by selecting tools or commands, or by positioning the virtual objects being manipulated) while the micrometric ("preferred") hand performs fine manipulation tasks. If each hand can then deal with only a single gesture style (for example, tapping or pressing versus dragging), the user's cognitive load may be reduced, making the software feel "effortless" and more efficient to use.

6.3 Future work

6.3.1 Two-handed modal interface

In this study, only two conditions (one-handed with latching buttons and two-handed with quasimodal buttons) were compared, which leaves open the question of how much of the difference resulted from using two hands, and how much resulted from avoiding modes. A one-handed quasimodal interface would almost certainly be too problematic to use at the scale of a tablet screen (reaching all points on the screen while holding one finger on a stationary button would be challenging for most hands), but a two-handed modal interface could easily be done. It is expected that much of the speed improvement seen here with the bimanual quasimodal technique will transfer to a modal version; however, this arrangement maps less well to the way we normally use our hands in bimanual tasks, with the macrometric hand providing a frame of reference for the micrometric, so we would expect an increase in cognitive load and higher rates of errors. The other benefits of eliminating modes, such as faster recovery from distractions, would also be lost. A study that involved longer tasks, and a distractor element, could look further into this aspect.

6.3.2 Dealing with occlusion

One unforeseen issue that arose during the study sessions was that of occlusion of the second dot as a result of its position relative to the initial dot. Because we used (constrained) random locations, and because the second dot of each pair did not appear until the starting dot was touched, there were instances where the second dot was hidden by the user's hand, forcing the user to swivel his or her hand in order to find the dot. (Recall that one had to maintain contact with the initial dot in order for the second dot to appear.) Also, the dots which caused problems were different for different people, due to differing hand angles and which hand they were using, so it was not just a matter of replacing the problematic pairs. However, as all users had the same disadvantage, and as the issue would generally reappear with the same pairs in both conditions (recall that a subject was shown the same sequences in the same order for each input style), unless someone was able to memorize the sequences on one showing (which no one showed any signs of having done), any impact on the results should be negligible.

The intention behind this design was to enforce a consistent set of motions between all participants (which we lost by not having a regular pattern), removing an element of variation between participants and between conditions (for the same participant). However, the occlusion problem was a minor source of frustration for users, and probably accounted for a good number of the outlier connection-step times, so it would be worth trying other options to produce the desired effect, such as colouring only one of the dots, or dimming the second dot until the first was touched. (Occlusion could still be an issue at the start of a new pair, but we observed that participants tended to keep their "drawing" hand moving between steps—kind of circling above the screen—rather than just lifting straight up, so the issue might be less pronounced there.)

It is also debatable as to whether this method for constraining users provided any value over showing both dots and allowing the user the freedom to choose the direction of the line. (This is something else that might be tested in another study.)

Another option would be to show the entire sequence of dots (and perhaps use a regular pattern, as in Dillon et al. [5]) to allow users to plan their moves, reducing the observation and decision-making times between and during each step. The concern there was that some participants would plan their moves ahead and others would not, making between-subject comparisons harder. However, as our primary interest lay in the difference in performance between conditions for an individual participant, such a scheme would likely have worked just as well, and been easier on participants.

6.3.3 Better isolation of condition differences

Dillon et al. [5] had users perform the study task with and without command selection, in order to isolate the "time cost of command selection". This includes both the time to select the command and the time to resume the primary task. When designing the study, it was deemed unnecessary to have participants perform an extra round of trials when the software could capture and separate the command-selection and drawing parts of each trial step, however, in retrospect, leaving out the no-command condition was probably a mistake.

Although we have separated out the time spend on drawing, there is an observation and planning component of the primary task that gets lumped in with the colour-selection timing in this arrangement, which would still be present in the no-command condition, and which should be largely unchanged between the two conditions we tested. We get close enough to see that there is a real difference between the two techniques being studied here, but it's likely that the quantitative results we obtained still somewhat *understates* the true difference on the command-selection portion by itself. Repeating the experiment with a monochrome condition (eliminating the color selection step) would provide a more accurate assessment of the time cost for each of the tool selection techniques.

6.3.4 Larger touchscreens

Although our experiment was performed using a tablet, these techniques may also be used with tabletop and wall-mounted surfaces (and may, in fact, be better suited for such). However, with a larger surface area, a movable palette, akin to the Toolglass interface, may be required. This allows the palette to be kept within the user's locus of attention, whereas palettes fixed to the sides of the work area may become too far away to reach easily.

6.3.5 Recruitment

It must be noted that the study sample consists largely of tech-savvy individuals (university science students and tech-sector workers), and thus the results may not be as generalizable as intended. The hope had been to include a wider range of touchscreen expertise, but given the broad use of smartphones and tablets in our culture today, it is becoming increasingly difficult to find many “novice” touchscreen users.

That said, the primary audience for this sort of technique is likely the very people who were so keen to participate in the study, so the sampling can still be considered representative of the target population. Nevertheless, it might be of some value to perform further sessions with novice and inexperienced touchscreen users to verify that the findings hold for that group as well.

6.3.6 Applications

The original impetus for this study was to determine the best input technique to use for an experimental touchscreen visual programming language, and the results of this experiment will be used to inform the design of the next phase of that project. Further experiments will be required to help choose techniques for navigating through hierarchically organized program code and for rapidly finding and referencing remotely defined program objects.

Some thought has also been given to making a version of the study software that can be released for open download, in order to collect data and feedback from a much wider audience.

A number of the study participants suggested other applications for the bimanual technique, primarily things like graphical editors, animation design, presentation builders, and so on—anything that has traditionally used palettes of tools and requires frequent switching, or software that separates the parameter controls from the objects in the editor space.

One variation that was suggested was to use the “off” hand to activate an overlay (such as continuous colour sliders or two-dimensional object libraries), operate the controls or drag things from the overlay with the “preferred” hand, and have the overlay disappear automatically when the first touch is released. Having such overlays activated in a quasimodal fashion (as opposed to using a latching-style button to toggle them on and off) makes it easier to exit the overlay mode without making a selection, and faster to resume working after an interruption that occurs while the overlay has been activated.

6.4 Research contributions

We have presented a novel two-handed user interface for touchscreens that has the potential to improve user productivity for some types of applications, and which people seem to like using. It mimics the way we tend to use our hands in day-to-day manual activities, which makes it very easy to learn, even for novice computer users. It also addresses the problem of mode errors by adapting quasimodal activation to touchscreen devices. The kinaesthetic feedback from holding a finger to the screen to activate a tool or command provides a salient reminder of the presence of the mode, and it becomes trivial to enter a known application state—one just lifts that hand away from the screen, an automatic gesture when an interruption occurs.

Our study results have shown that, by dedicating one hand to command selection and thereby avoiding the extra movement and attention switches that are required when a single hand does double duty, this style of interface reduces the cost of command selection and can result in an overall performance improvement in mode-heavy applications. And that users can see such an immediate effect (10% to 30% reductions in command selection time), with no training or practice, is very promising.

The study also confirmed our expectation that users would find this a more natural way to work, as predicted by Guiard’s Kinematic Chain model. In fact, our study participants’ enthusiasm for the technique surpassed our expectations, suggesting that converting people from the status quo touch UI may not be as challenging in this case as it usually is.

6.5 Conclusion

The astounding rate of touchscreen tablet adoption has resulted in an interface landscape that is markedly different to that of even a few years ago, and much of the pioneering research into bimanual computer interfaces has not yet been applied within this new setting. Up until now, very little of our interaction with these newer devices has used more than one or two fingers of one hand, nor do the interface designs stray far from GUIs based on the mouse's single point of interaction and latched modes. The richness of interaction possible when both hands can be used together in a coordinated fashion has not yet been explored.

The results of this study, while preliminary, provide some insight into how to build more efficient and immersive touch-based interfaces. In the right environment, people seem ready to adopt novel interfaces and would like their interactions with digital technology to feel more natural and integrated with their other activities. The system proposed here validates the use of Guiard's Kinematic Chain Model in user interface design, and is a first step at breaking the tyranny of the tap, opening the doors to further experimentation.

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Appendix A

Study Materials

Background Questionnaire

Please check only one answer for each question. If you have any concerns about a question or wish to clarify your response, please use the space beside or below the question or the back of the sheet to provide any additional notes.

1. What is your age?

- ☐ 18–24
- ☐ 25–34
- ☐ 35–44
- ☐ 45–54
- ☐ 55 or over

2. What is your gender?

- ☐ Male
- ☐ Female

3. Which hand do you use to write with?

- ☐ Left
- ☐ Right
- ☐ Either

4. How would you assess your technical knowledge of computers?

- ☐ 5 – Advanced understanding at the operating system level
- ☐ 4 – Basic knowledge at the operating system level
- ☐ 3 – Advanced user of software (web browsers, e-mail, etc.)
- ☐ 2 – Regular user of software (web browsers, e-mail, etc.)
- ☐ 1 – Sporadic user of software (web browsers, e-mail, etc.)

5. How would you assess your experience with touchscreen computing devices, such as tablet computers (e.g. Apple iPad), smartphones, media players, etc.?

- ☐ 5 – Expert user, e.g. a year or more of (more or less) daily use
- ☐ 4 – Very comfortable, e.g. less than a year or less frequent usage
- ☐ 3 – New owner, still getting to know it
- ☐ 2 – Have used one briefly on a few occasions
- ☐ 1 – Never used one

6. Other than using a keyboard, have you used any computer interfaces designed specifically to be used with two hands at once?

- ☐ Yes, ____
  Please list the input device(s) used
- ☐ No
- ☐ I'm not sure

Post-Condition Questionnaire

For each of the statements below, please rate your level of agreement or disagreement with respect to the input technique you just used by circling the appropriate number below each statement.

1. I found this input technique easy to use.

strongly disagree neutral strongly agree

1 2 3 4 5 6 7

2. I learned this input technique quickly.

strongly disagree neutral strongly agree

1 2 3 4 5 6 7

3. I was able to get the task done quickly using this technique.

strongly disagree neutral strongly agree

1 2 3 4 5 6 7

4. I didn't have to think very much about what to do with my hands, so I could focus on the task itself.

strongly disagree neutral strongly agree

1 2 3 4 5 6 7

5. I did not feel any hand/arm fatigue or discomfort while using this technique.

strongly disagree neutral strongly agree

1 2 3 4 5 6 7

6. I enjoyed using this technique.

strongly disagree neutral strongly agree

1 2 3 4 5 6 7

Post-Trial Interview Questions

These questions are meant to guide a semi-structured interview to be conducted with the participant after completing the task portion of the session. The interviewer will also ask other questions based on previous responses, and may rephrase questions to aid comprehension, if necessary.

1. Which of the input techniques did you like the *best* (if any)?

- ☐ One-handed
- ☐ Two-handed

Why do you feel that way?

2. Which of the input techniques felt the *fastest*?

- ☐ One-handed
- ☐ Two-handed

Why do you think that was?

3. Which of the techniques felt the most natural?

- ☐ One-handed
- ☐ Two-handed

Why?

4. In what ways do you think these interface designs could be improved? (alt: How could these interfaces be improved?)

5. For what kinds of applications or situations do you think the two-handed techniques would be most appropriate? ... least appropriate?

6. Tell me about your previous experience with touchscreen interfaces. What devices do you use or have you used in the past? (Look at background questionnaire for anything unusual.)

Appendix B

Research Ethics Board Approval

Social Sciences & Humanities Research Ethics Board
Annual Renewal - Letter of Approval

October 02, 2015

Mr Michael Hackett
Computer Science\Computer Science

Dear Michael,

REB #:	2012-2779
Project Title:	Input Techniques for Touchscreen Tablets
Expiry Date:	October 09, 2016

The Social Sciences & Humanities Research Ethics Board has reviewed your annual report and has approved continuing approval of this project up to the expiry date (above).

REB approval is only effective for up to 12 months (as per TCPS article 6.14) after which the research requires additional review and approval for a subsequent period of up to 12 months. Prior to the expiry of this approval, you are responsible for submitting an annual report to further renew REB approval. Forms are available on the Research Ethics website.

I am also including a reminder (below) of your other on-going research ethics responsibilities with respect to this research.

Sincerely,

Dr. Karen Beazley, Chair