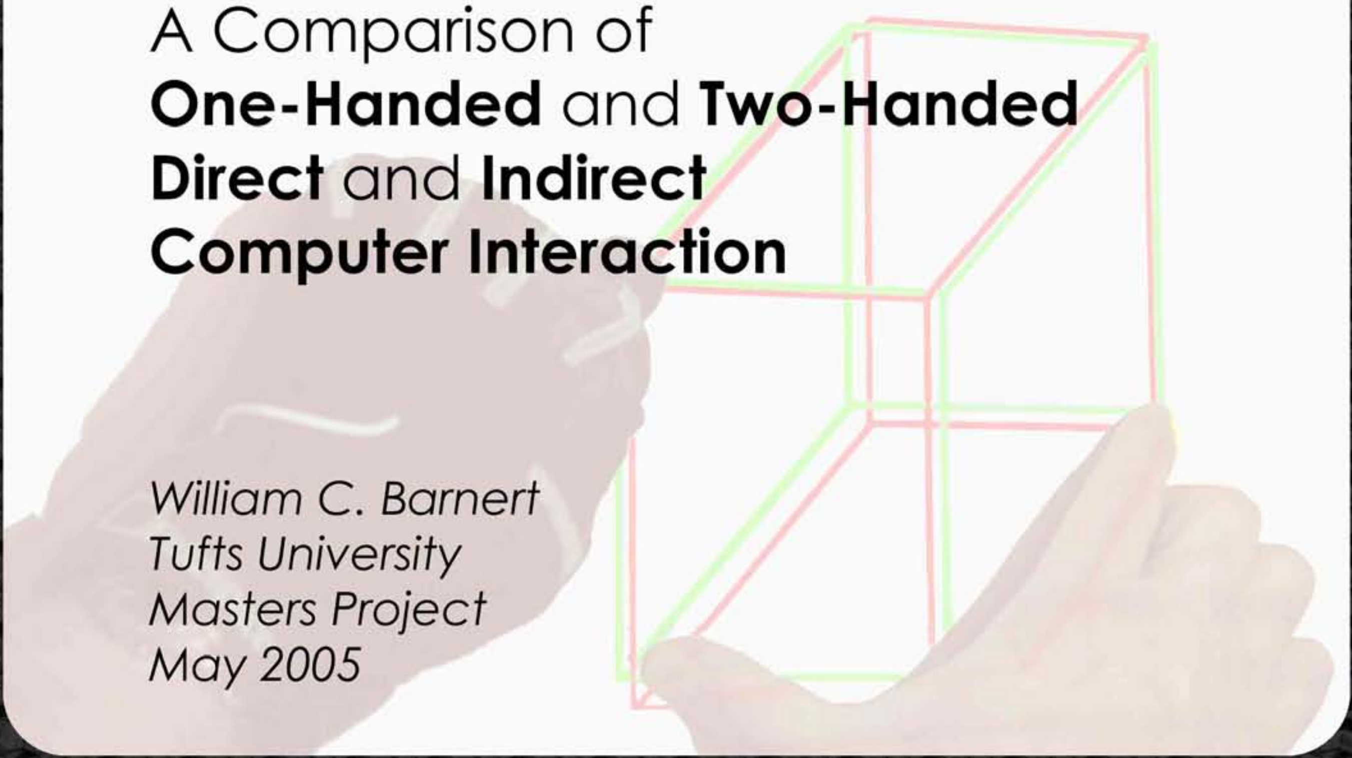
A Comparison of **One-Handed** and **Two-Handed** **Direct** and **Indirect** **Computer Interaction**



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Masters Project
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Abstract

This study compares the differences in efficiency, productivity and user preferences of different computer interaction techniques, independently varying the number of hands used and whether the interaction was direct or indirect. In this way, we will see (A) how bimanual interaction compares with unimanual interaction, (B) how direct interaction compares with indirect interaction, and (C), if there is a clear advantage to one technique over the other in both (A) and (B), whether the advantages in each category can be combined. We find that indirect interaction techniques outperform direct interaction techniques. Interestingly, we find that within indirect techniques, bimanual outperforms unimanual, but within direct techniques, unimanual outperforms bimanual. The use of a second hand *enhances* performance and enjoyment using indirect techniques, but *diminishes* both using direct. We show that with even minimal familiarity with a bimanual indirect interaction technique, performance with it increases further, and it is more likely to be selected subjectively as the favorite method. We argue that if bimanual indirect methods were made readily available, they would be embraced by most computer users after a very short learning curve.

Introduction

Standardization is a wonderful thing. Without standards, you would not be able to plug your appliances in when you got home unless you built your own plugs. However, standardization can have some drawbacks as well. Unless you change the standard, you cannot move forward with ideas that exceed the limitations of the standard. Currently, the standard hardware interface to most computers is a combination of a keyboard and a mouse (or a mouse-substitute like a trackball). The keyboard has keys that allow you to type as you would on a typewriter, plus many additional keys like the Function Keys, Arrow Keys, often a numeric keypad, and special function keys like the ESCAPE, CONTROL and ALT keys. The mouse – used as a unimanual indirect interaction device – allows you to move a cursor over a Graphical User Interface (GUI), and with the use of buttons or other selection devices on the mouse, to indicate to the software what you want to do and when. The mouse is used in conjunction with the GUI: rarely does the hand controlling the mouse act independently of the eyes watching the screen. This standard pair of input devices has done a lot towards making today's user interfaces much more user-friendly than the keyboard-limited command line interfaces of the past. But it is also holding us back from the advantages of using both hands to operate graphical tools.

In the almost twenty years since the seminal paper on two-handed computer input by Buxton and Myers (1986) much research has gone into studying the benefits of two-handed input, and most of it has shown clear benefits. In this paper, I review much of this research, and add my own. I was interested in seeing how the non-traditional interaction techniques — direct manipulation of the display and the use of two hands — affected the user's experience, both in performance, and emotionally. By independently varying both the number of hands used and the choice of direct or indirect interaction, I intended to discover whether there was any cumulative enhancements that could be combined using direct two-handed interaction. What I found, however, was that the use of hands directly on a screen for drawing tasks did not perform as well as the indirect methods, and the more hands, the less well it performed. As with many previous studies, bimanual indirect interaction outperformed unimanual indirect interaction. This, combined with the comparison between direct and indirect techniques leads me to argue for the adoption of two-handed input as a standard. I also discuss some promising new products and some future research in this field.

Existing Research

Buxton and Myers (1986) did two experiments to compare the performance of bimanual input to unimanual input. Their first experiment used two input devices: a mouse-like device in one hand to control the position of a square on the screen, and a simple one-dimensional slider in the other hand to control the size of the square. The assigned task was to size and position a given square to a specified size and location. They deliberately tried to bias the test subjects to do the tasks in series, hoping to see them discover on their own that the tasks could be done more efficiently in parallel, and indeed this is what they found. They also found that the speed of the task was strongly correlated to how much parallelism the user employed.

Their second experiment compared one-handed and two-handed techniques for locating and selecting text. The user would have to scroll through a document to locate the text to select. In the one-handed test, the mouse-like device was used with a visible scrollbar on the screen, and the user could either scroll smoothly or in quantized jumps by clicking in different parts of the scrollbar widget. In the two-handed test, two touch-sensitive strips were used by the second hand to scroll, one strip for smooth scrolling and one for page jumps. The subjects were instructed to go for speed, and were even given chances to beat their own time. The subjects using the two-handed system performed better than those using only one.

This is not surprising. Humans often use two hands simultaneously to do two separate but related tasks, and so the subjects did not have to teach themselves the concept of doing this, only the specific details. While driving a standard transmission car, you might be steering with one hand while shifting with the other (and depressing the clutch with your foot). A pianist might be playing with one hand while turning the pages with the other. A symphony conductor might use one hand to keep the beat while using the other to signal changes in dynamics. And even in computer interfaces, we often use a limited form of two-handed input when we CONTROL-click on a mouse (although this was not common in 1986).

A study at the *Centre d'Études Navigation Aérienne* in Toulouse, France (Chatty 1994) made the point that while two-handed input was desirable, no task should *depend* on two-handed input, as the user (in this case air traffic controllers) may also need to do something with the other hand like hold a sheet of paper. In this study, they found that even the simple addition of a second mouse and the software to support it to modify the radar image (zoom, time, etc.) was worthwhile.

Yves Guiard (Guiard, Y., (1987) Asymmetric division of labor in human skilled bimanual action: The kinematic chain as model, *Journal of Motor Behavior 19*, 486-517, as cited in Kabbash et al (1994)) studied the way people use their two hands, and it turns out that even though most people have a dominant hand and a non-dominant hand, it is not true that the dominant hand is better at everything than the non-dominant hand. They each have their own special skills, and the two hands depend on each other in three ways: (1) The non-dominant hand "sets the frame of reference for the action" of the dominant hand. (e.g.: a right-handed person might hold a wine bottle in their left hand, while their right hand screws out the cork.) (2) The sequence of motions is from the non-dominant hand to the dominant one. (e.g.: in the example above, your left hand will grab the bottle *before* your right hand gets involved.) (3) The non-dominant hand has a coarser "granularity of action" (e.g.: it doesn't matter exactly *where* you hold the wine bottle, but once placed, the corkscrew *must* go into the cork.) Many designers have used these dependencies as guidelines to creating well-designed two-handed interfaces, and the studies done on them have proven this to be a good decision.

Perhaps one of the best two-handed input designs comes from a collaboration between Xerox PARC, the University of Toronto, and the University of Washington. Bier, Stone, Pier, Buxton and DeRose (1993) designed an elegant system that made use of the different talents of each hand, and had several other advantages as well. Imagine the fairly common task of using a graphical design tool to draw a diagram. Most design tools using one-handed mouse input force the mouse to do double-duty: you use it on the drawing itself to draw lines, shapes, curves, etc., as well as to select objects or areas. But you also use it to select tools and details from a toolbar. To draw a red square, you might first have to move the mouse to the toolbar to select "Square", then move it back to the canvas to draw the square, then move it back to the toolbar to select

"Red". The Toolglass technique that they describe replaces the toolbar with a see-through (semi-transparent) area that can be moved with the second hand. So in the example above, without taking your dominant hand or eyes off of the canvas that you are drawing, you could move the Toolglass over the canvas, select "Square" to draw, draw the square, and then in a single click "Click-through" the "Red" on the Toolglass onto the square you drew to make it red. This system not only illustrates the uses of two-handed input, it also saves screen space, by putting the Toolglass *over* the canvas. Figures 1, 2 and 3 illustrate some color-changing Toolglass widgets. Similar widgets can be used to select shapes, font styles, etc., and many of these widgets can be combined on a larger sheet that can be moved as one by the non-dominant hand. Thus, attention can remain focused on the task, while the non-dominant hand can bring the needed tools into the area of focus, rather than diverting attention to the toolbar.

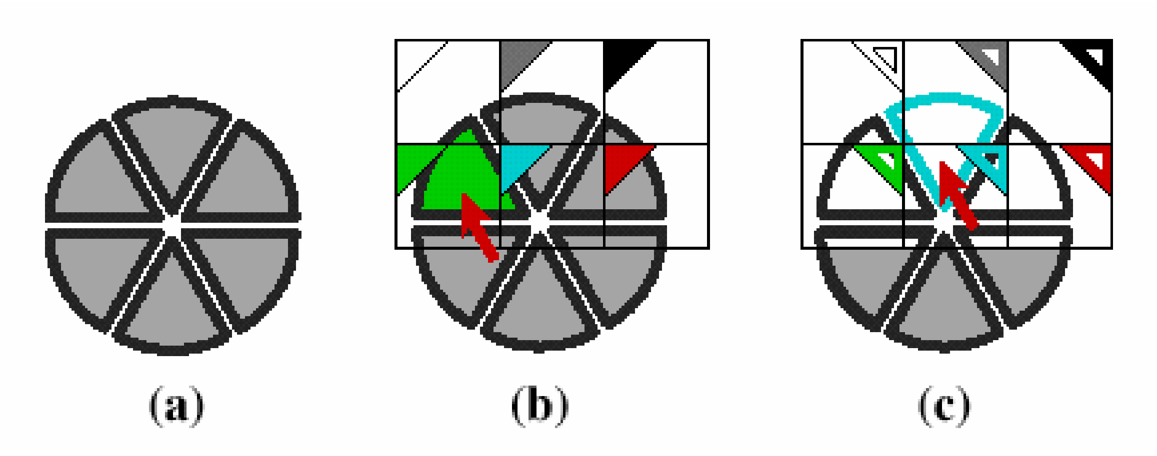

Figure 1: An example of a Toolglass color-changing widget (from Bier et al, 1993). Figure 1a shows a drawing of six uncolored wedges. In Figure 1b, the user can position the Toolglass color widget over the drawing with their non-dominant hand, and "click-through" it to change the color of one wedge to green. Figure 1c shows a similar widget for changing the outline color of an object, which has the additional feature that it is a filtering "lens" through which only borders are seen. This has both the cognitive benefit of reminding the user which tool they are using and the visual benefit of seeing borders that might have been obscured by other objects.

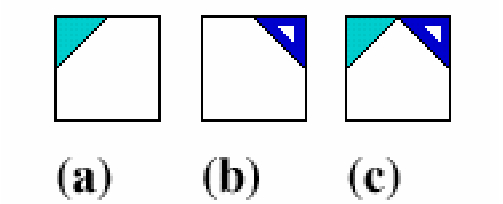

Figure 2: Toolglass widgets can be combined (from Bier et al, 1993). Figures 2a and 2b are color-changing widgets for an object's body and border respectively. Figure 2c shows a combined widget that can change an object's body to cyan and its border to blue with a single "click-through". Once created, the combined widget can be reused multiple times.

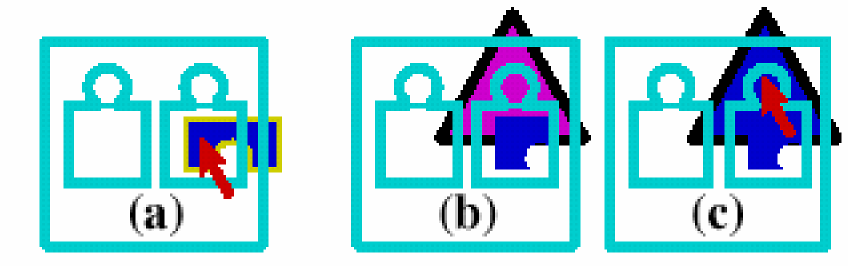

Figure 3: A Toolglass rubbing widget (from Bier et al, 1993) is a tool that can copy the color of one object to another. In figure 3a, the user has positioned the widget with their non-dominant hand so that clicking through the tombstone "rubs off" the blue behind it. Notice in figure 3b that the shape of the rubbed color is also maintained as a reminder of where it came from. In figure 3c, the user clicks through the blue-labeled tombstone onto the triangle below to change it to blue. The second tombstone represents the idea that multiple colors can be rubbed onto one widget, so that you can transport a set of colors from one drawing (or area) to another.

Later studies, such as that by Kabbash, Buxton and Sellen (1994) compared the Toolglass technique to one-handed techniques and other two-handed techniques: some using the two hands to control independent tasks, and some (like Toolglass) where the two hands are "asymmetrically dependent", where the actions of one hand depended on the actions of the other. The authors set out to "understand the motor and cognitive load imposed by different kinds of two-handed techniques", and hoped to prove that asymmetrically dependent techniques would result "in significantly improved performance without imposing additional cognitive load". The Toolglass technique was found to be superior to the other techniques. The test subjects did significantly better with the Toolglass technique on a number of tasks, even though they had received little or no training. Their other technique comparisons, however, showed that just adding the second hand, for example for some tasks, adding a second mouse and allowing the two hands to share the workload can even *lower* a person's performance, even though they need to move the mice less far. They compared the inefficiency of using two hands to do two independent tasks to "tapping the head while rubbing the stomach": controlling the two independent hands simultaneously is more confusing than helpful.

One of the experiments done by Kabbash et al (1994) was to draw a series of line segments from a starting point to a series of dots that would appear. The subject was told to draw the line segment in the color of the destination dot. A menu of colors was used to select the color of the next line segment to be drawn. The color menu was always movable on the screen. In the one-handed technique, the user could only use the one mouse to move the menu, select a color, or draw the line, so all must be done sequentially. In a simple two-handed version, the user had access to two mice, but they each did exactly what the one mouse could do, so they were still limited to sequential operations, except that they could use one hand to move the color menu and one to select and draw. The two asymmetrically dependent tasks were the Toolglass technique, which did the best, and a technique they called the "Palette menu", where the second hand directly controlled the location of the color menu, rather than a cursor that could be used to move it. As expected, the Toolglass technique performed the best, but the Palette menu technique was far behind it, and in some rankings came in last. As part of the study, the subjects were asked to evaluate the techniques, and most ranked the Toolglass as the best, but only one ranked the one-handed technique as worst. The evaluation showed the subjects were confused about how best to use the palette. One of the additional reasons the authors suggested for the Toolglass technique doing so well was that by not having to move their eyes off the task at hand, the subjects never had to reassimilate the context of the drawing.

There are obvious manual advantages of using two hands: just as "two heads are better than one", two hands can do more at once than one can, and two hands have twice as many simultaneous degrees of freedom, as Buxton and Myers' (1986) positioning and scaling experiment described above demonstrates. But there are clearly demonstrable cognitive benefits to two-handed input for many applications as well. Leganchuk et al (1998) set out to test this by finding if two hands were better able to "chunk" actions in a natural way. They theorized that this would lead to improved performance for three reasons: (1) it would "reduce and externalize the load of planning/visualization" by allowing the user to treat what would be several tasks using one-handed input as one single more complex operation using two. (2) "Rapid feedback of manipulation results in a higher level of task", by getting immediate visual feedback on every move made, the user is better able to visualize the path to task completion. And (3) they cited a paper by D. Kirsh and P. Maglio (On distinguishing epistemic from pragmatic action. *Cognitive Science 18, 4*, p. 513-549) that demonstrated how "human actions ... can be performed to facilitate cognition". They ran several tests, including a variation on the positioning and scaling test, where a subject had to draw a bounding box around a shape, either a minimum enclosure box containing as little else besides the enclosed object as possible, or a task where they had to draw a box around one object avoiding other objects, where it was not always easy to guess where the corner(s) of the box would be until it was drawn. The results of their experiments bore out their hypothesis, and chunking of actions was observed using the two-handed techniques, leading to increased efficiency of the tasks. And the more demanding the cognitive task, the bigger difference there was between the techniques.

They also performed a follow-up experiment to see if practice would benefit performance. They used the results of the first experiment to select the most demanding cognitive loads. Not only did the two-handed technique continue to outperform the one-handed technique, but practice using the two-handed technique lead to a higher level of improvement than practice using the one-handed technique.

Where Are We Now?

In summary, numerous experiments have consistently shown both a motor and cognitive benefit to using two-handed input. So why don't we do it? I believe the biggest hurdle is the adoption of additional hardware. When people write software for PC's or other computers, they write them for the hardware that everyone already has. A program that needs an additional input device will not have much of a market. And the reverse is also true: until there is lots of software that takes advantage of a second input device, where is the incentive to buy one? Video games are one area where this has been somewhat overcome. Systems that are dedicated to video games come with more complex (but still standardized) input devices, consisting of joysticks, and thumb and finger controls for both hands. But these have been optimized for games, and even these rarely give the user position control of two separate objects. Usually you have one position control and a series of command buttons.

Where To Next?

While today, most people consider the mouse to be an integral part of a computer interface, it took a long time to get from invention to your desk. The first mouse was a wooden box with two metal wheels on the bottom and a single button on top, designed (along with the first GUI) by Douglas Engelbart at Stanford in 1964. But it wasn't until the early eighties when the Macintosh started shipping with them, and later other computers running Microsoft Windows, that they started to become ubiquitous in our computing environment. And the amount of GUI software out there now that is supported by the keyboard-plus-mouse combination is a lot larger than what was supported before the Macintosh by command line interfaces. So I am not discouraged that the idea of a second input device has not yet taken hold.

I recently had a chance to glimpse the future of bimanual indirect input. A company called Digital ArtForms, Inc. introduced a two-handed system for three-dimensional drawing, and I saw a demo of it. Using two hand-held devices that contain gyroscopes so the computer always knows where they have been moved or turned *(see Figure 4)* you can manipulate objects in a 3D virtual world *(see Figure 5)*.

Figure 4: Digital ArtForms gyroscopic input devices. (Digital ArtForms, Inc. n.d./2004).

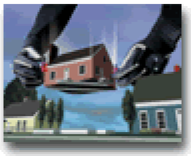

Figure 5: A stylized example of software using Digital ArtForms gyroscopic input devices. (Digital ArtForms, Inc. n.d./2003).

While this is big step forward, I do not see this as the "next big thing", as the advantages of simply adding a low-cost second mouse or trackball to a system seem to me to outweigh the cost of this special hardware, except for designers who need to work in 3D, such as architects.

Two-Handed Tangible User Interfaces

One new area that two-handed interfaces *is* taking hold is in the area of Tangible User Interfaces, or TUI's. While there is a tangible aspect to interfaces like the Digital ArtForms device, or even a mouse, TUI refers to interfaces where you are interacting directly with physical objects that represent the data. Almost by definition, TUI's can be manipulated by two hands, as it is the manipulation of the object that matters, not how you do it.

A company called MolySim makes a product called LuxMol for modeling simulations of molecules that allow you to physically build a molecule from separate pieces that represent individual atoms. The atoms can only be combined in ways that are valid in the real world, and each element of the model that you build "has knowledge of its own state and its immediate neighbors" (MolySim n.d./2004) A wireless connection allows the software simulation to immediately reflect the state of the model that you are building for analysis and display.

Another interesting tangible interface is a research project by Ben-Joseph et al (2001) called the Luminous Planning Table. This table is both an input and an output device to a computer program: input because a set of video cameras is monitoring what occurs on it, and output because a projector is projecting a display onto it. The flat table surface represents a land area. An urban planner could take a map of a city area and place it on the table, then place a model of a proposed building onto the table. The model is tagged so that the computer can recognize it from the video input, and the computer calculates where the shadows of the building would be at any given time of the day (or other factors like where the wind would blow), and projects this information onto the map. The planner can then move the model, or add others, and check the shadow patterns at different times of the day to see what would happen. Decisions about what to build where could then be made based on this information. While it is certainly possible to get this information using existing non-tangible interfaces, the immediate feedback of the table, coupled with the ability for teams to work together on the same model, proved to be of strong benefit. And the learning curve for this tool is very quick, as the interface so closely resembles the natural world, augmented.

Experiment

This section describes an experiment designed to compare the differences in efficiency, productivity and user preferences of different computer interaction techniques, independently varying the number of hands used and whether the interaction was direct or indirect. In this way, we will see (A) how bimanual interaction compares with unimanual interaction, (B) how direct interaction compares with indirect interaction, and (C), if there is a clear advantage to one technique over the other in both (A) and (B), whether the advantages in each category can be combined. The experiment is done in two phases.

Participants

Participants were recruited from a broad spectrum of society. There were a total of thirty-one subjects, twenty-six men and five women, ranging in age from nineteen to over sixty. Most (94%) were either right-handed or generally used the right hand for mousing. Only 6% reported that they used the left hand for mousing. Twenty-four of the subjects participated in Phase I of the study, and seven in Phase II.

Apparatus/Environment

The tests were performed using software designed for this study, running on a computer with a DiamondTouch™ screen by Mitsubishi Electric Research Labs (MERL). The computer display was projected from above onto the screen (25.5”x19.5”), which was mounted horizontally at a height of 28” from the floor. The mouse and mouse pad were to the right on a desk of height 26.5” from the floor *(see Figure 6).* Speed and accuracy data were collected automatically by the software. Additional data were collected orally by the researcher. The tests were performed in the HCI Lab at Tufts University.

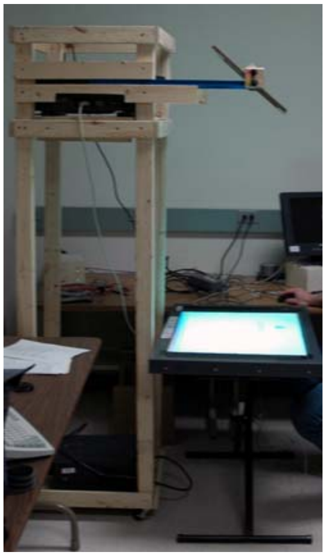

Figure 6: The study environment, showing the DiamondTouch™ screen with image projected from above.

Procedure: Phase I

Each participant was given a simple game-like task to complete using four different methods, and had to complete the task ten times in a row for each method. Twenty-four subjects were used so that each possible order of the four methods would be used exactly once. Which order was used for which subject was determined at random.

The basic task was to draw a red cube on top of a green cube, trying to match the width, height, depth and location as closely as possible *(see Figure 7)*. Subjects were told that the data being collected "includes both speed and accuracy for completing each task," but were not given instructions as to which should be considered more important.

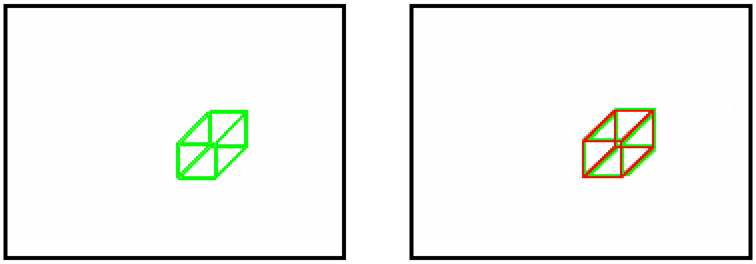

Figure 7: Subject would be presented with a green cube, and be asked to draw a red cube on top of it.

Before each method, the participants were shown a short slideshow illustrating how to use that method, and were given one (or more, if they requested) training rounds to try out the method with no data being collected. Once the training round was over, a series of ten cubes would appear at different locations on the screen, with edge sizes ranging from 0.75 to 3.75 inches. Each set of ten cubes for a method contained the same ten cube sizes, but in a different order, and at different locations.

Time was measured in seconds from the moment the green target cube appeared until the red cube had both its base and height set. Accuracy Error was calculated as the sum of the distances (in pixels) between the red drawn cube and the green target of three representative corners.

After the four methods were complete, participants were asked to guess which method they did the best in, whether they thought they performed better for speed or for accuracy, which they preferred the most, whether they had any difficulties using any of the methods (and what those difficulties were), and whether any of the methods seemed familiar to them.

The Four Methods

The four methods used to draw the red cube were:

- **Unimanual Indirect [1I], or "Mouse" method:**
  Subject would create the base of the cube by clicking at the lower left corner, dragging to the far right corner, and releasing, and then would set the height by clicking again (and optionally dragging to adjust). *(See Figure 8.)*
- **Bimanual Indirect [2I], or "Mouse+Slider" method:**
  Subject would create the base as in the Mouse method, but would set and adjust the height using their left hand on a slider projected on the screen. Some subjects chose to do this simultaneously, some chose to do it in sequence. *(See Figure 9.)*
- **Unimanual Direct [1D], or "One Hand Touch" method:**
  Subject would create the base of the cube using any two fingers of their right hand, defining (and adjusting) the lower left corner and the far right corner of the cube, and then would use a single finger from the same hand to set and adjust the height. *(See Figure 10.)*
- **Bimanual Direct [2D], or "Two Hand Touch" method:**
  Subject would create the base as in the One Hand Touch method, but would set and adjust the height using their left hand directly on the screen. As with the Mouse+Slider method, some subjects chose to do this simultaneously, some chose to do this in sequence. *(See Figure 11.)*

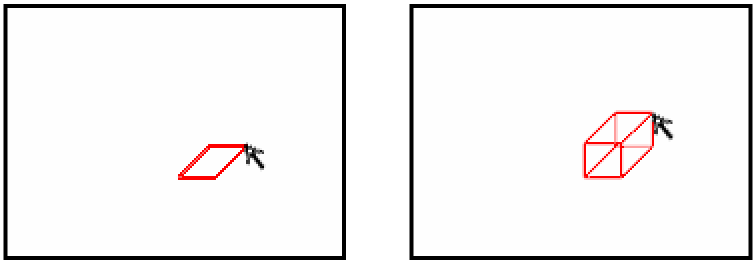

Figure 8: Unimanual Indirect Method (Mouse):
Click, drag & release to draw the base; then click (and optionally drag & release) to set the height.

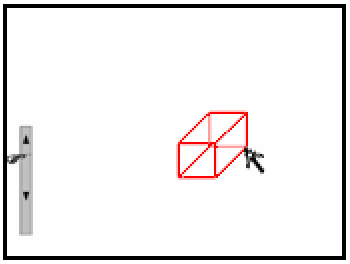

Figure 9: Bimanual Indirect Method (Mouse+Slider):
Click, drag & release to draw the base; set height with left hand on slider.

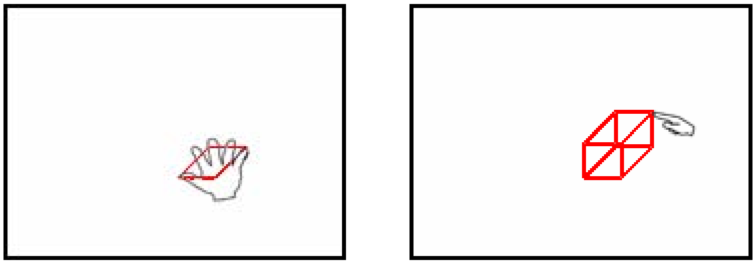

Figure 10: Unimanual Direct Method (One Hand Touch):
Use any two fingers to draw the base; then use index finger to set the height.

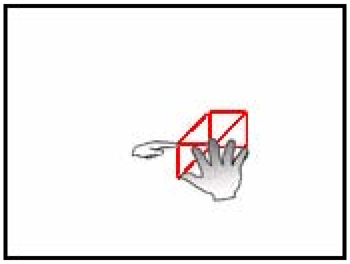

Figure 11: Bimanual Direct Method (Two Hand Touch):
Use any two fingers on right hand to draw the base; use index finger on left hand to set the height.

For the Bimanual Direct method, the participant wore an insulating FakeSpace™ glove on their left hand, with the index finger wired in to the DiamondTouch™ screen, so that the screen could differentiate the left hand from the right *(see Figure 12)*.

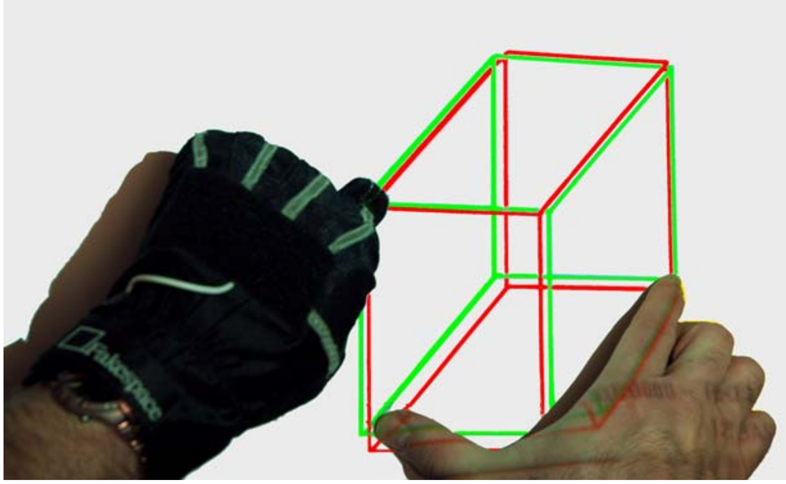

Figure 12: For the Two Hand Touch method, participants wore a glove on the left hand.
(Photo retouched to eliminate glare and artifacts.)

Procedure: Phase II

Phase II was essentially identical to Phase I except for three things:

1. The participants were asked to perform the test in five sets, not four.
2. The order of the methods was limited to one of two orders:
    - 1I – 2I – 1D – 2D – 2I
    - 1D – 2D – 1I – 2I – 2D
3. The participants were strongly encouraged to do each of the bimanual methods in parallel, not in sequence.

Note that the unimanual version of each method (direct or indirect) always preceded the bimanual version of that method, and it is always the bimanual version of the first method that is repeated as the fifth method.

Results

Phase I

In Phase I of the experiment, a number of interesting trends were noticed. Looking only at the quantitative data collected automatically *(see Figure 13 & Figure 14)*, it is noted that participants did much better, for both speed and accuracy, with the two direct methods than with the two indirect methods. Within the direct methods, the bimanual was less accurate than the unimanual method, and usually slower. Within the indirect methods, the bimanual method was faster for some people and slower for others, more accurate for some people and less accurate for others.

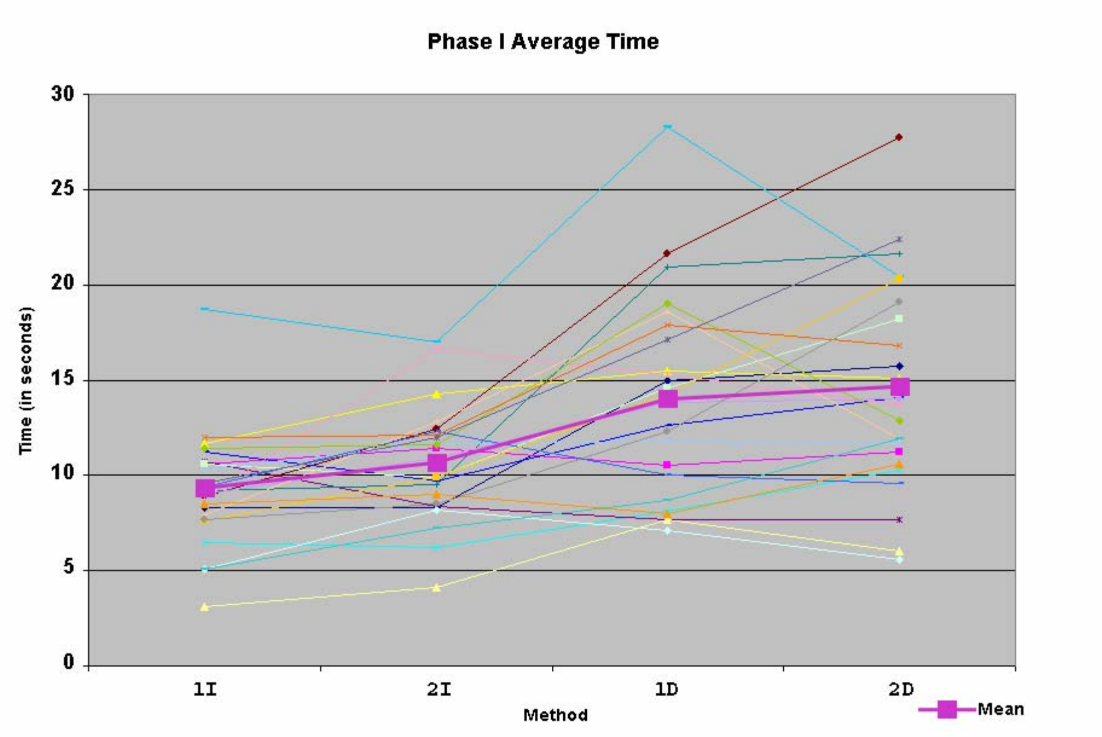

Figure 13: Phase I Time Scores for Each Method. Thin lines each represent one individual participant. Thick purple line is the mean of all participants. (Extremely long individual times that did not reflect actual performance time have been filtered as outliers.)

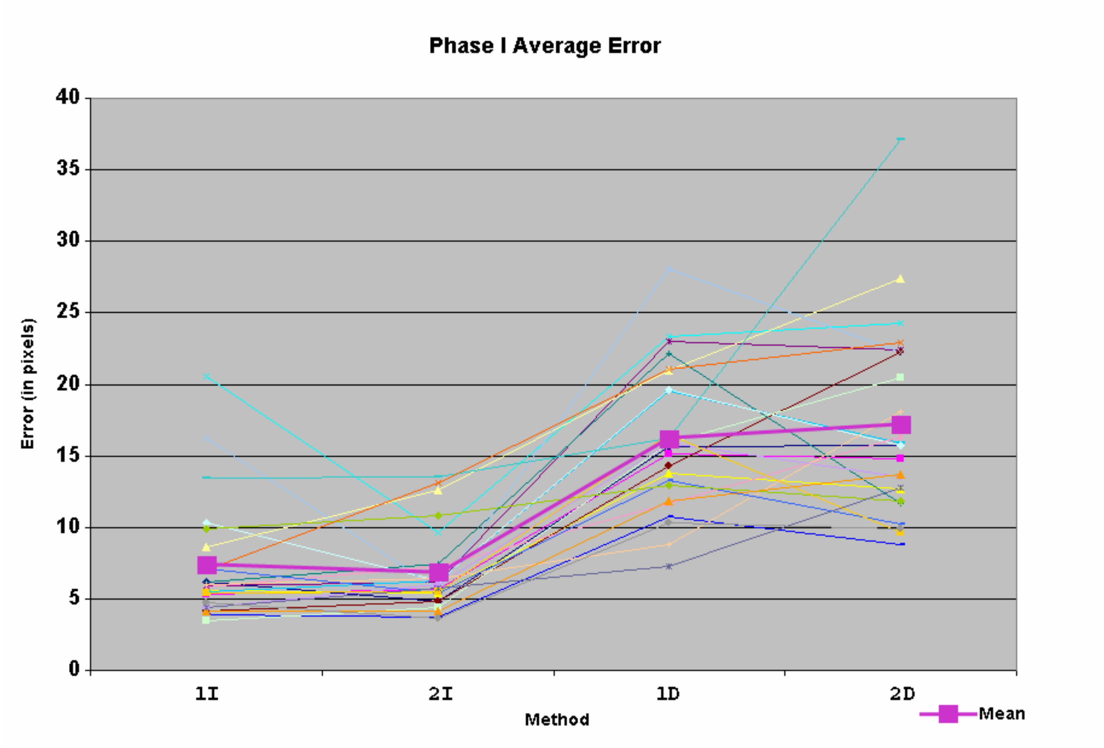

Figure 14: Phase I Error Scores for Each Method. Thin lines each represent one individual participant. Thick purple line is the mean of all participants.

From the visual evidence, we make six hypotheses:

H1: The mean completion time for Indirect Interaction is *lower* than for Direct Interaction.

H2: The mean error for Indirect Interaction is *lower* than for Direct Interaction.

H3: Within Indirect Interaction, the mean completion time for One-Handed Interaction is *lower* than for Two-Handed Interaction.

H4: Within Indirect Interaction, the mean error for One-Handed Interaction is *higher* than for Two-Handed Interaction.

H5: Within Direct Interaction, the mean completion time for One-Handed Interaction is *lower* than for Two-Handed Interaction.

H6: Within Direct Interaction, the mean error for One-Handed Interaction is *lower* than for Two-Handed Interaction.

Statistical analysis of the results for the Time and Error scores for Phase I (see Appendix A for details) shows evidence to statistically support hypotheses H1, H2, H3 and H5, but not H4 or H6. To summarize:

- **Direct vs. Indirect (Time and Error)**: Subjects were faster and more accurate using Indirect Interaction than using Direct Interaction.
- **Number of Hands (Time):** Subjects were slightly faster using one hand than two hands.
- **Number of Hands (Error**): We assume that the variability in Error is entirely explained by Direct vs. Indirect interaction,. and the number of hands is not significant.

To compare the quantitative data collected automatically with the subjective data collected orally, Figure 15 shows each participant represented by a letter from A-X, and indicates which method or methods they selected or scored highest in, for four metrics. The first two columns, Time Score & Error Score, reflect which method that participant scored the best in (lowest value), with scores within a small range considered equal[1]. The third and fourth columns represent the participants' answers to the questions "Which of the four methods would you guess you did the best in?" and "Which of the four methods did you enjoy the most?". There is only a slight correlation between which methods any particular participant did well in and which they preferred, and both of the bimanual methods were selected as "most enjoyed" more often than they were either guessed best, or actually performed best in.

Participants who chose to perform the bimanual indirect method (Mouse+Slider) by adjusting both the base and the height of the cube in parallel were more likely to select this method as their favorite than participants who created the base first, then set the height.

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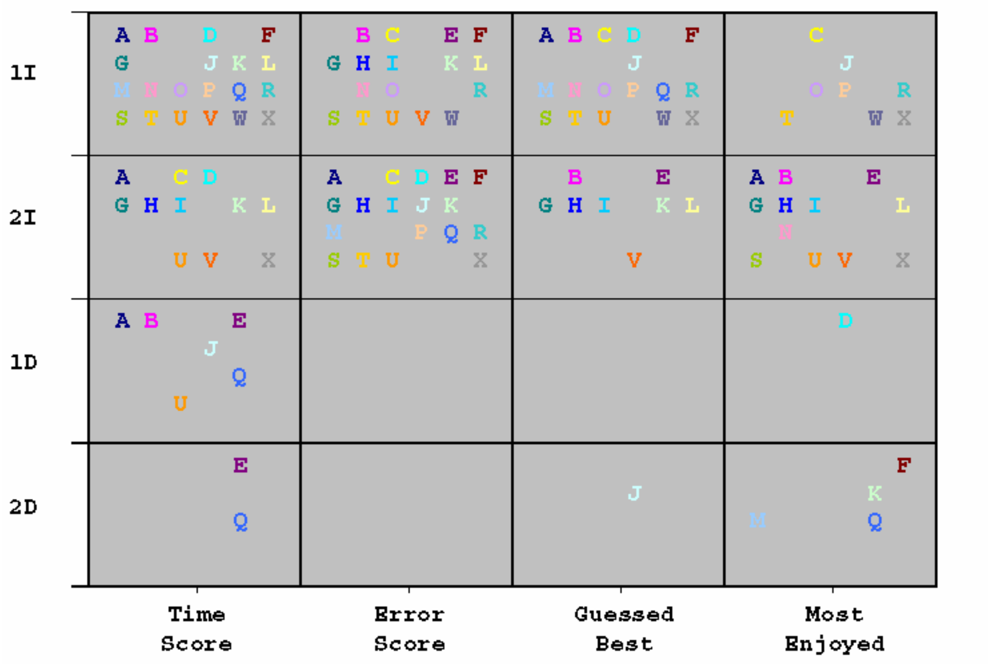
[1] Mean values within 1 second for Time or 2 pixels for Error were considered equivalent. Subjective answers were considered equivalent if the participant gave two answers to the question. This is why a letter may appear twice in one column. If the scores for two methods were equivalent, that letter will appear twice in one column.



	Time Score	Error Score	Guessed Best	Most Enjoyed
1I	A B D F G J K L M N O P Q R S T U V W X	B C E F G H I K L N O R S T U V W	A B C D F J M N O P Q R S T U W X	C J O P R T W X
2I	A C D G H I K L U V X	A C D E F G H I J K M P Q R S T U X	B E G H I K L V	A B E G H I L N S U V X
1D	A B E J Q U			D
2D	E Q		J	F K M Q

Figure 15: Phase I Summary of Results for each Participant

Phase II

In Phase II of the experiment, in which one of the bimanual methods was repeated, almost all subjects improved their speed the second time they performed the repeated method. For the direct interaction methods, they were also significantly more accurate. For the indirect interaction methods, the accuracy was about the same. Almost all participants who were faster with the unimanual version than the bimanual version of the method that was repeated improved their time score for the bimanual version the second time to as good or better than the unimanual version. *(See Figure 16 & Figure 17.)*

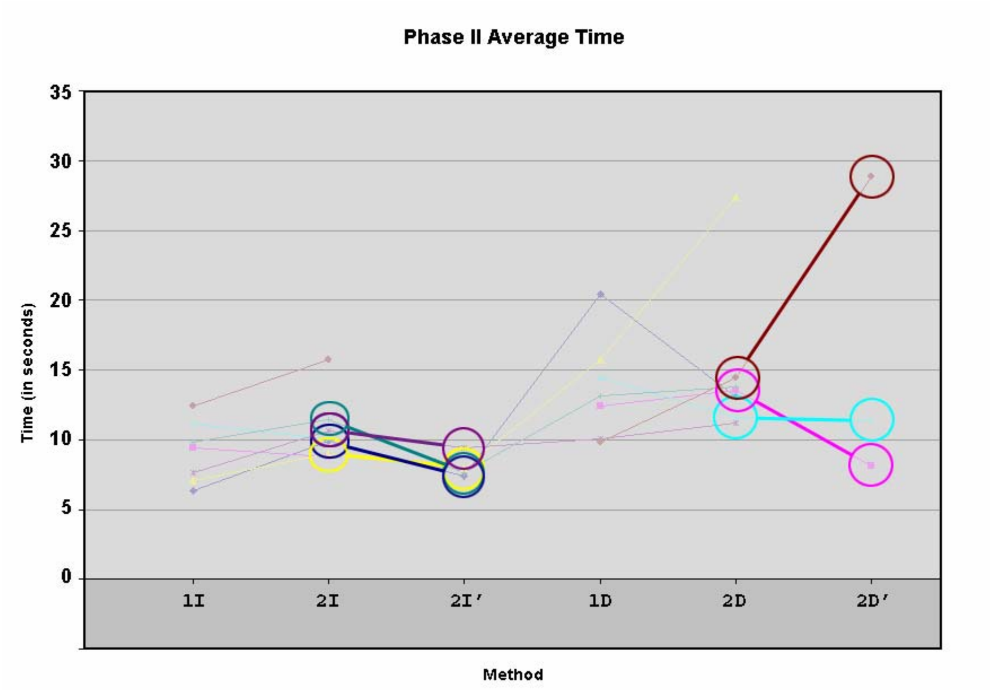


Figure 16: Phase II Time Scores for Each Method. The order of the methods displayed does not represent the actual order, but in all cases 1I preceded 2I, which preceded 2I' (representing the second bimanual indirect method), and 1D preceded 2D, which preceded 2D'. Thus the circled points and the lines connecting them represent the improvement between the first and second tries at whichever bimanual method that participant repeated. Each participant repeated either the bimanual indirect or the bimanual direct, but not both. This is why each line either skips over 2I', or ends before 2D'.

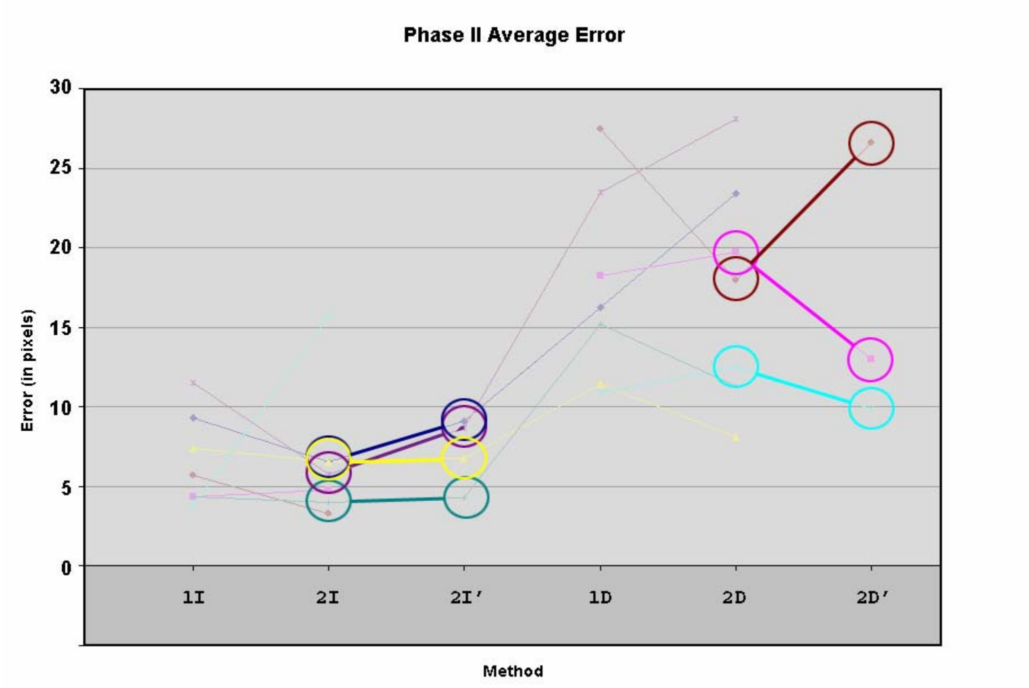
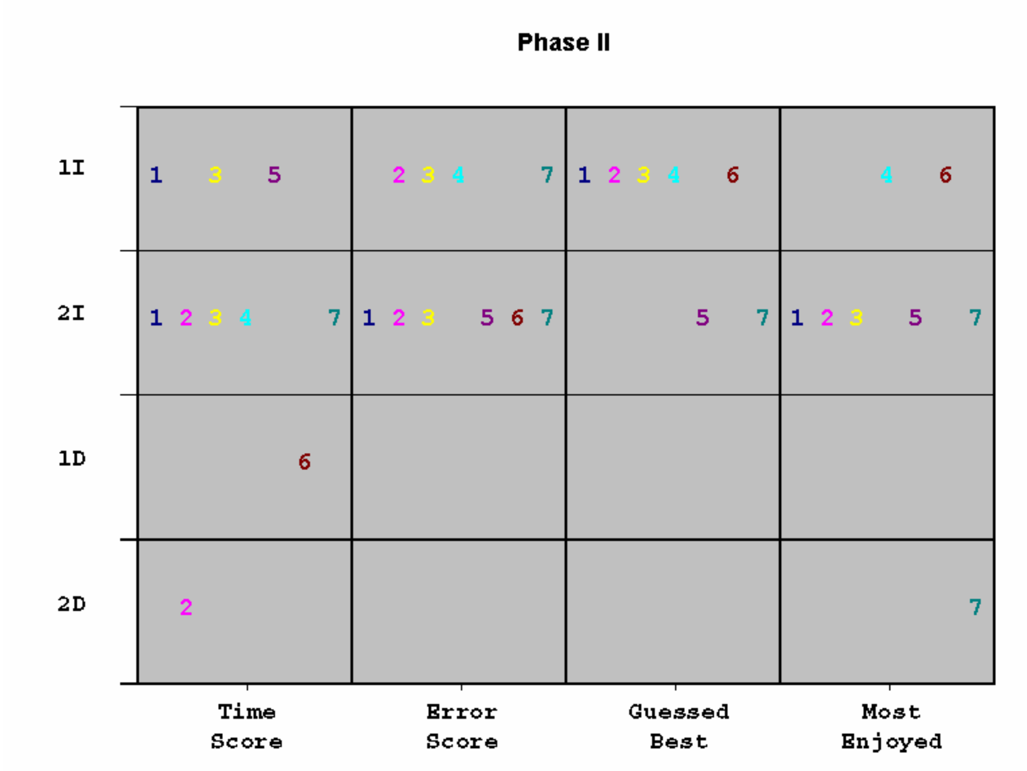


Figure 17: Phase II Error Scores for Each Method. The circled points and the lines connecting them represent the improvement between the first and second tries at whichever bimanual method that participant repeated. See the notes in Figure 16 for additional details.

Both the popularity of the bimanual indirect method and its effectiveness increased in Phase II when the participants were given instructions to perform it in parallel, and were given more time to practice the method and get acclimated to it. This was not true for the bimanual direct method. Figure 18 summarizes the results for Phase II. Although many people believed they had done better with the Mouse alone method (1I), most, including all who repeated it, chose the Mouse+Slider method (2I) as their favorite. The direct methods did not fare well at all.



	Time Score	Error Score	Guessed Best	Most Enjoyed
1I	1 3 5	2 3 4 7	1 2 3 4 6	4 6
2I	1 2 3 4 7	1 2 3 5 6 7	5 7	1 2 3 5 7
1D	6			
2D	2			7

Figure 18: Phase II Summary of Results for each Participant. The odd-numbered participants repeated the Mouse+Slider method (2I), the even-numbered participants repeated the Two Hand Touch method (2D). Although many people believed they had done better with the Mouse alone method (1I), most, including all who repeated it, chose the Mouse+Slider method (2I) as their favorite.

The number of participants in Phase II was not statistically significant.

Discussion

Physical Drawbacks of Direct Interaction

Numerous problems were reported by the participants, or observed by the researcher, when the participants were using either of the direct interaction methods. The first is that the tip of one's finger is much less precise than the tip of a cursor. The phrase "my fat fingers" was used in frustration by many participants. Secondly, because the human body is not transparent, the participants' hands were often blocking their view of the screen. Lastly, because the screen being used was a top-projected horizontal surface, the participants' hands – and even sometimes their heads – cast shadows. *(See photo in Figure 12 above, and discussion on "Suggested Future Studies" below.)*

Parallel Performance

When using either of the bimanual interaction methods, participants who chose to do the two parts of the task (creating the base and setting the height) in parallel performed better than those who chose to perform them in series. They were also more likely to select the bimanual method as the one they enjoyed the most. This was noticed in Phase I of the experiment, where participants were encouraged to use the method in any manner they chose, and Phase II was partly designed to examine this further. Were there people who tended to gravitate toward parallel interaction when given the choice, and therefore more likely to select the bimanual method as their favorite, or does using parallel interaction enhance the experience for all? All participants were encouraged in Phase II to do the bimanual methods in parallel, and this, combined with the ability to get more familiar with the method *(see discussion on "Familiarity with Interaction Method" below)* raised both the performance and the enjoyment scores for all.

Two Hands Enhance Performance in Indirect Interaction, Detract in Direct

Two of the (incorrect) assumptions of the researcher when first designing this experiment were that people would probably do better on the bimanual version of each method than on the unimanual version, and better on the direct methods than the indirect. In addition to wanting to test this theory, the researcher wanted to determine, if true, whether the two enhancements were additive or not *(see Figure 19)*.

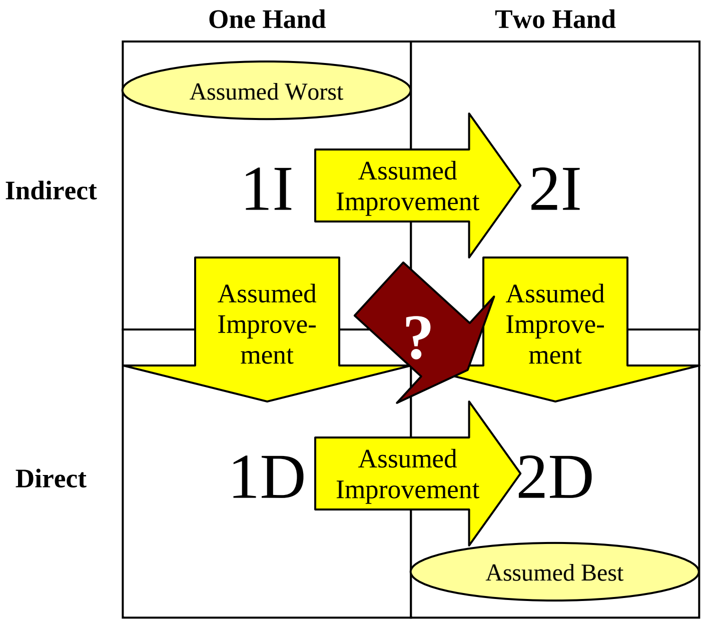


Figure 19: If all four of the assumed improvements turned out to be true (bimanual always better than unimanual, direct always better than indirect), then bimanual direct should be the best and unimanual indirect should be the worst. But would the two improvements add together? Would they enhance each other more than that? Less than that? Would they cancel each other out?

But few of the assumptions held. The assumption that bimanual would be better than unimanual was the only one that proved true, and only for indirect interaction. Because of the problems with direct interaction discussed above *("Physical Drawbacks of Direct Interaction")*, direct interaction did not prove better than indirect, and when using the indirect methods, the problems were magnified with two hands, so unimanual direct interaction proved better than bimanual *(see Figure 20)*. The use of a second hand *enhances* performance and enjoyment using indirect techniques, but *diminishes* both using direct.

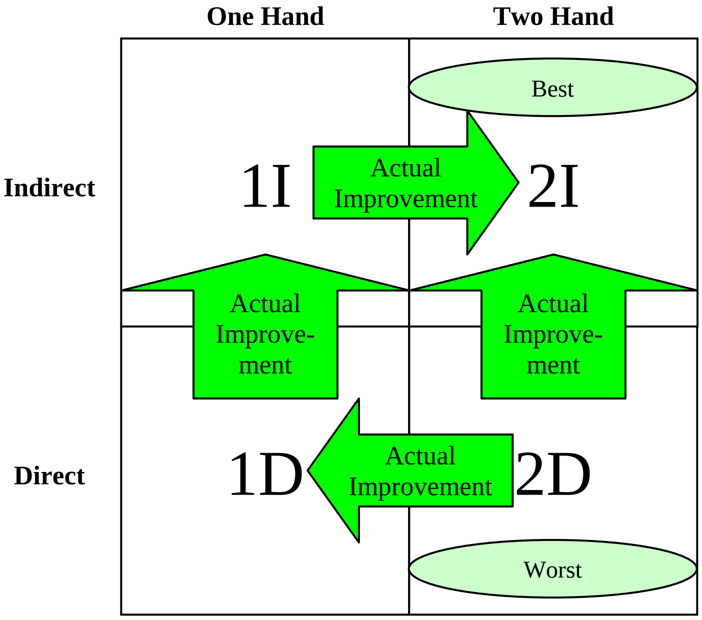


Figure 20: In reality, there were no two actual improvements that could be added. Although indirect was always better than direct, unimanual was better in direct interaction, and bimanual was better in indirect.

Individual Techniques

In addition to the parallelism discussed above, individual participants varied widely in their choice of techniques. For example, when using the Mouse method *(see Figure 8)*, the basic task was to click at the lower left corner of the base, drag the mouse to the far right corner of the base and release, then click to set (and optionally drag to adjust) the height. When creating the base, some participants dragged diagonally but straight through the base, while others chose to "trace" along the green cube's edges by dragging straight right along one edge, then straight up along another *(see Figure 21)*. When setting the height, some chose to quickly click and release, increasing their speed, while others chose to click and hold for a second to adjust before releasing, thus increasing their accuracy. Still others chose to "trace" along the right edge of the green cube and then release at the top. The other methods showed similar variety in techniques.

When creating the base, some participants dragged the mouse diagonally through the base …

… while others chose to “trace” along the green cube’s edges.

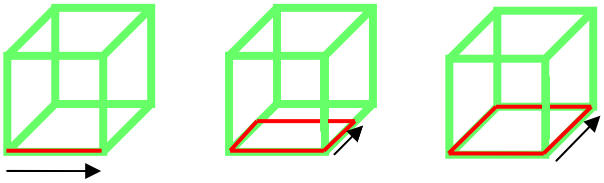


Figure 21: Different participants chose to do parts of the tasks in very different ways.

This variance made a true comparison of the methods difficult. Phase II helped eliminate some of this variance by giving stronger instructions on the technique to use. Those that used a more parallel technique for the Mouse+Slider method, either by choice or by instruction, performed better with it than those who did not, and also reported that they enjoyed it more.

Familiarity with Interaction Method

Many of the participants reported that they selected the Mouse method as their favorite, or guessed that they did better in that method, because of their familiarity with it. The other methods were generally unfamiliar, although some reported enjoying them for that reason. Both intuition and the results of Phase II would lead one to believe that performance using the Mouse+Slider method would continue to improve as the user’s familiarity with it increased.

Gestural Drawing

The most novel interaction technique in this study was the idea of drawing directly on a screen using a predefined gesture. In both of the direct interaction methods, the base of the cube was drawn by touching the screen with any two fingers, which would define two corners of the base. The user could then adjust both the size and location of the base simultaneously as if they were holding a rubber-band-like parallelogram. Participants' reactions to this method varied widely, from those who really enjoyed it ("This is fun!") to those who were extremely agitated by it ("Ugh! I hate this!").

Real World Applications

The level of detail required for drawing programs will probably continue to necessitate indirect interaction methods, or stylus-based direct methods. The use of one's hands directly on a drawing surface is not practical.

As in many of the previous studies referenced earlier, we have shown distinct advantages to bimanual indirect interaction, and continue to advocate for its adoption in common practice. The increase in performance and enjoyment for the Mouse+Slider method in Phase II leads the author to believe that if bimanual indirect methods were made readily available, they would be embraced by most computer users, after a very short learning curve.

Suggested Future Studies

To further test the differences seen in Phase II from Phase I, an additional test similar to Phase II with a large enough number of samples to be of statistical significance would be beneficial. Phrasing the subjective questions to be more specific, and requiring the participants to make a single selection for each, would allow the subjective data to be subject to statistical analysis as well.

To better test the benefits of direct interaction, a touch-screen monitor or rear-projecting screen would eliminate the shadows, but not the problem of the user’s hands blocking the view. The use of a fine-point stylus (single pixel diameter) could ameliorate both the blocked view problem and the problem of “fat fingers” having difficulty selecting at the pixel level.

To test whether variance in technique is beneficial or detrimental to learning a new interaction method, two groups of people could be tested, allowing them to use any technique they think of. In one of these groups, repeat the test twice more with the same instructions. With the other group, teach them a highly efficient parallel technique, and test them twice more. Compare the results of the third test in each group to see whether the people who chose non-parallel techniques in the first test improved more when repeating their own technique, or being taught the parallel technique.

An interesting longer-term study along these lines would be to teach two groups of people different techniques for the same task. The parallel technique should be harder to learn, but more efficient once you have learned it. After both groups have gotten used to doing the task over a period of time, see how many had switched techniques on their own. For those who had not switched techniques, teach them the other technique and ask them to use it for a while. Compare the results of those who learned the parallel technique first to those that switched to it later. Is it better to learn the easier technique first, then unlearn it to learn the parallel technique, or to learn the parallel technique from the beginning?

Acknowledgments

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Appendix A: Statistical Analysis in Detail

In this Appendix, the terms Time & Error refer to the raw Time (in seconds) and Error values (in pixels) as measured during the test. The terms LogTime and LogError refer to the natural log of Time and Error, and the terms NLTime and NLError refer to the normalized versions of LogTime and LogError, using the following equations:

$$NLTime = \frac{(LogTime - MeanPerPerson[LogTime])}{(StdDevPerPerson[LogTime])}$$

$$NLError = \frac{(LogError - MeanPerPerson[LogError])}{(StdDevPerPerson[LogError])}$$

Looking at the raw data *(see Figure 22)*, we see that both Time & Error are one-tailed distributions.

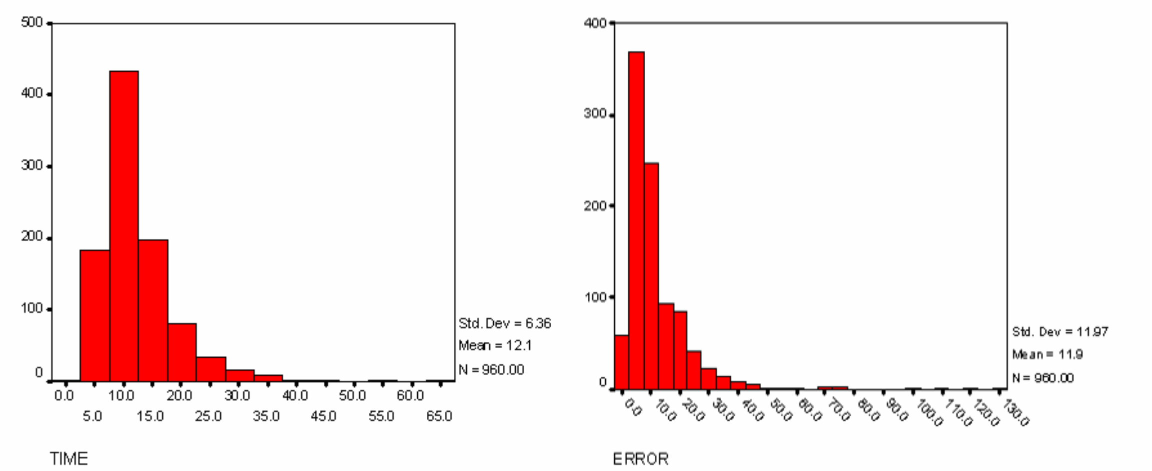

Figure 22: Both Time & Error are one-tailed distributions.

Taking the natural log of the raw data, we see a more symmetric distribution *(see Figure 23)*. Error values of zero were changed to values of one in this process to allow for the natural log to be taken. The error value is the sum of three error values, so a single-pixel error may be considered virtually identical to an error value of zero.

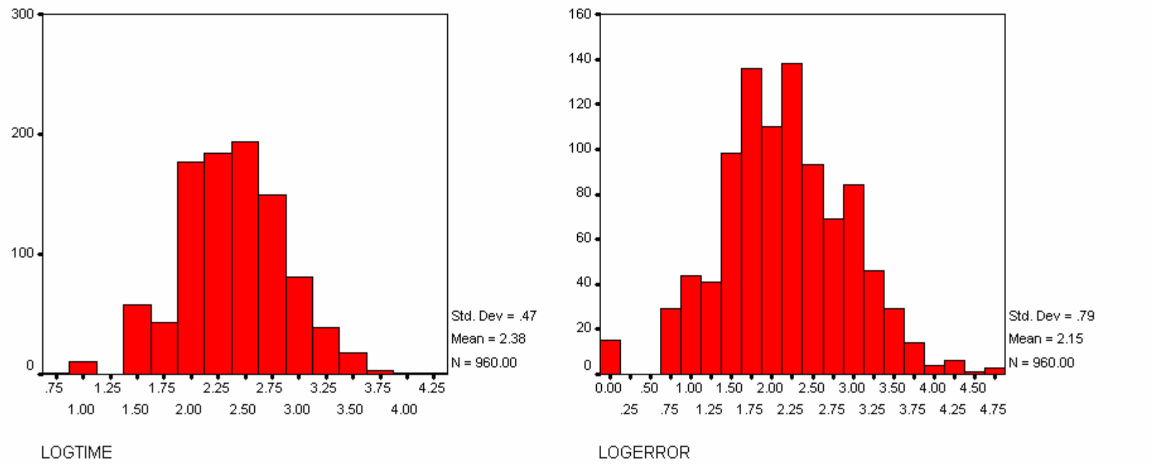

Figure 23: The Log of the Time & Error Functions.

Normalizing the Time and Error functions eliminates differences between subjects, and we see that we have a nice bell-curve normal distribution *(see Figure 24)*.

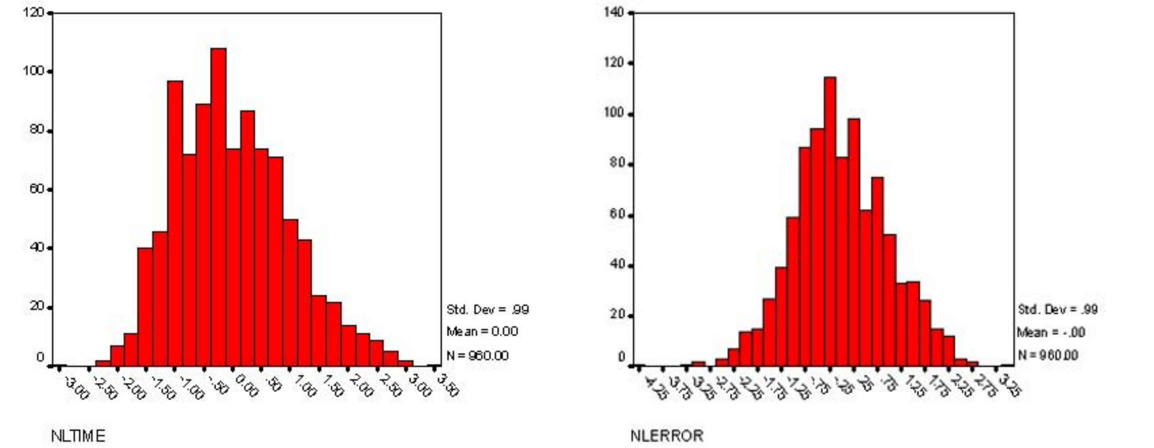

Figure 24: The Normalized Log of the Time & Error Functions.

To confirm that the Normalized Log functions are a normal distributions, a P-P plot is done on each *(see Figure 25)*. The near exact straight-line diagonal of these curves indicates a normal distribution. We also see in Table 1 that both NLTime and NLError have a Mean that is close to zero, and a Standard Deviation that is close to 1.

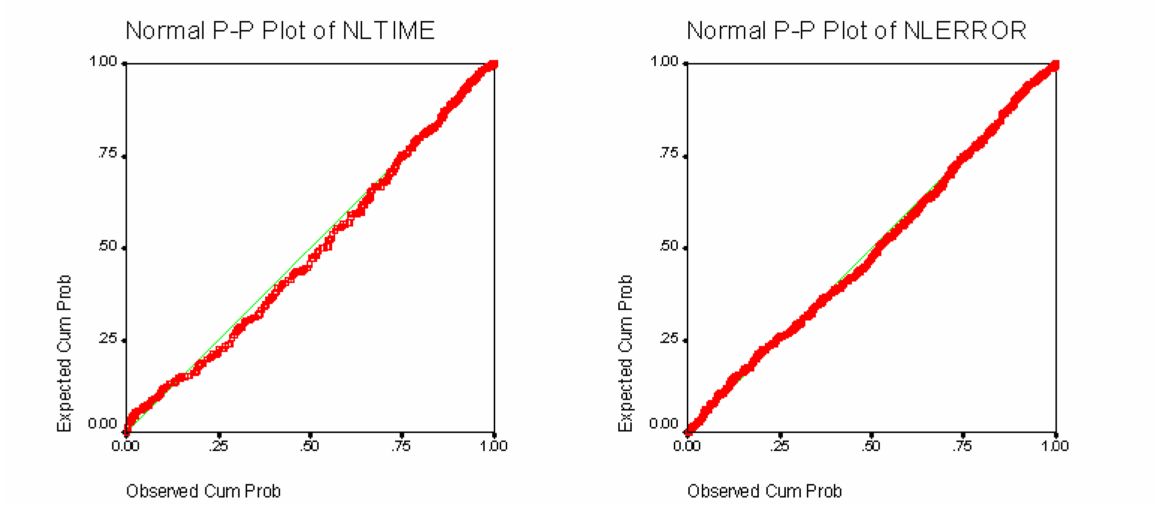

Figure 25: P-P Plots of NLTime and NLError.

Table 1: Descriptive Statistics for All Variables

	N	Minimum	Maximum	Mean	Std. Deviation
Time	960	2	65	12.09	6.36
Error	960	1.00	128.83	11.8609	11.9682
LogTime	960	.69	4.17	2.3789	.4711
LogError	960	.00	4.86	2.1534	.7866
NL Time	960	-2.92	3.44	-1.0417E-12	.9879
NL Error	960	-4.17	3.43	-3.0918E-03	.9920

An ANOVA by test subject also confirms that the Normalized Log versions of the metrics are the correct parameters to test. We see in Table 2 that the raw values (Time, Error) and the Log value (LogTime, LogError) show a significant difference between subjects (Sig=0.000), while the Normalized Log values (NLTime, NLError) show no difference between subjects (Sig=1.000).

Table 2: ANOVA by Test Subject

		Sum of Squares	df	Mean Square	F	Sig.
Time	Between Groups	11597.683	23	504.247	17.343	.000
	Within Groups	27214.250	936	29.075		
	Total	38811.933	959			
Error	Between Groups	13278.055	23	577.307	4.355	.000
	Within Groups	124088.142	936	132.573		
	Total	137366.197	959			
LogTime	Between Groups	87.776	23	3.816	28.572	.000
	Within Groups	125.022	936	.134		
	Total	212.798	959			
LogError	Between Groups	71.480	23	3.108	5.574	.000
	Within Groups	521.856	936	.558		
	Total	593.336	959			
NLTime	Between Groups	6.924E-18	23	3.010E-19	.000	1.000
	Within Groups	936.000	936	1.000		
	Total	936.000	959			
NLError	Between Groups	.211	23	9.177E-03	.009	1.000
	Within Groups	943.590	936	1.008		
	Total	943.801	959			

Now that we have confirmed that the Normalized Natural Log functions are normal distributions, we can perform Analysis of Variance (ANOVA) on them.. We do three analyses: One-way ANOVA by Number of Hands; One-way ANOVA comparing Direct-and.-Indirect; and Two-way ANOVA to compare the interaction between them.

One-way ANOVA by Number of Hands

We hypothesize:

$H0_{Time}$: That there is no difference in Time (NLTime) between one-handed and two-handed interaction.

$H1_{Time}$: That there is a difference in Time (NLTime) between one-handed and two-handed interaction.

$H0_{Error}$: That there is no difference in Error (NLError) between one-handed and two-handed interaction.

$H1_{Error}$: That there is a difference in Error (NLError) between one-handed and two-handed interaction.

Table 3: One-Way ANOVA by Number of Hands

		Sum of Squares	df	Mean Square	F	Sig.
Time	Between Groups	236.017	1	236.017	5.861	.016
	Within Groups	38575.917	958	40.267		
	Total	38811.933	959			
Error	Between Groups	10.061	1	10.061	.070	.791
	Within Groups	137356.136	958	143.378		
	Total	137366.197	959			
LogTime	Between Groups	1.563	1	1.563	7.089	.008
	Within Groups	211.235	958	.220		
	Total	212.798	959			
LogError	Between Groups	.307	1	.307	.495	.482
	Within Groups	593.029	958	.619		
	Total	593.336	959			
NLTime	Between Groups	10.943	1	10.943	11.332	.001
	Within Groups	925.057	958	.966		
	Total	936.000	959			
NLError	Between Groups	.457	1	.457	.464	.496
	Within Groups	943.343	958	.985		
	Total	943.801	959			

The calculated F for Time (NLTime) is 11.332, with a significance of 0.001. Therefore we reject $H0_{Time}$, and there is a significant difference between one-handed and two-handed interaction for Time.

The calculated F for Error (NLError) is 0.464, with a significance of 0.496, which is not low enough to reject $H0_{Error}$, and we cannot say whether there is a significant difference between one-handed and two-handed interaction for Error.

One-way ANOVA Comparing Direct-and-Indirect

We hypothesize:

$H0_{Time}$: That there is no difference in Time (NLTime) or Error (NLError) scores between direct and indirect interaction.

$H1_{Time}$: That there is a difference in Time (NLTime) or Error (NLError) scores between direct and indirect interaction.

$H0_{Error}$: That there is no difference in Time (NLTime) or Error (NLError) scores between direct and indirect interaction.

$H1_{Error}$: That there is a difference in Time (NLTime) or Error (NLError) scores between direct and indirect interaction.

Table 4: One-Way ANOVA Comparing Direct and Indirect

		Sum of Squares	df	Mean Square	F	Sig.
Time	Between Groups	4550.104	1	4550.104	127.226	.000
	Within Groups	34261.829	958	35.764		
	Total	38811.933	959			
Error	Between Groups	22070.042	1	22070.042	183.381	.000
	Within Groups	115296.155	958	120.351		
	Total	137366.197	959			
LogTime	Between Groups	25.436	1	25.436	130.059	.000
	Within Groups	187.361	958	.196		
	Total	212.798	959			
LogError	Between Groups	161.230	1	161.230	357.455	.000
	Within Groups	432.106	958	.451		
	Total	593.336	959			
NLTime	Between Groups	159.585	1	159.585	196.908	.000
	Within Groups	776.415	958	.810		
	Total	936.000	959			
NLError	Between Groups	292.408	1	292.408	430.042	.000
	Within Groups	651.393	958	.680		
	Total	943.801	959			

The calculated F for Time (NLTime) is 196.908, with a significance of 0.000. Therefore we reject $H0_{Time}$, and there is a significant difference between direct and indirect interaction for Time.

The calculated F for Error (NLError) is 430.042, with a significance of 0.000. Therefore we reject $H0_{Error}$, and there is a significant difference between direct and indirect interaction for Error.

Two-way ANOVA

We hypothesize:

$H0_{Time}$: That there is no interaction between the number of hands used and direct vs. indirect interaction for Time (NLTime) or Error (NLError).

$H1_{Time}$: That there is an interaction between the number of hands used and direct vs. indirect interaction for Time (NLTime) or Error (NLError).

$H0_{Error}$: That there is no interaction between the number of hands used and direct vs. indirect interaction for Time (NLTime) or Error (NLError).

$H1_{Error}$: That there is an interaction between the number of hands used and direct vs. indirect interaction for Time (NLTime) or Error (NLError).

Table 5: Two-Way ANOVA: Tests of Between Subjects Effects

Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	Time	145203.225	4	36300.806	1021.632	.000
	Error	157248.726	4	39312.181	326.316	.000
	LogTime	5461.241	4	1365.310	7073.487	.000
	LogError	4613.182	4	1153.295	2553.442	.000
	NLTime	181.796	4	45.449	57.609	.000
	NLError	292.874	4	73.219	107.533	.000
Number of Hands	Time	236.017	1	236.017	6.642	.010
	Error	10.061	1	10.061	.084	.773
	LogTime	1.563	1	1.563	8.098	.005
	LogError	.307	1	.307	.679	.410
	NLTime	10.943	1	10.943	13.870	.000
	NLError	.457	1	.457	.672	.413
Direct vs. Indirect	Time	4550.104	1	4550.104	128.056	.000
	Error	22070.042	1	22070.042	183.195	.000
	LogTime	25.436	1	25.436	131.782	.000
	LogError	161.230	1	161.230	356.969	.000
	NLTime	159.585	1	159.585	202.283	.000
	NLError	292.408	1	292.408	429.446	.000
Number of Hands * Direct vs. Indirect	Time	57.038	1	57.038	1.605	.205
	Error	114.057	1	114.057	.947	.331
	LogTime	1.273	1	1.273	6.596	.010
	LogError	9.228E-03	1	9.228E-03	.020	.886
	NLTime	11.269	1	11.269	14.284	.000
	NLError	2.986E-04	1	2.986E-04	.000	.983
Error	Time	33968.775	956	35.532		
	Error	115172.036	956	120.473		
	LogTime	184.525	956	.193		
	LogError	431.790	956	.452		
	NLTime	754.204	956	.789		
	NLError	650.935	956	.681		
Total	Time	179172.000	960			
	Error	272420.762	960			
	LogTime	5645.766	960			
	LogError	5044.972	960			
	NLTime	936.000	960			
	NLError	943.810	960			

The calculated F for the interaction effect for Time (NLTime) is 14.284, with a significance of 0.000. Therefore we reject $H0_{Time}$, and there is a significant interaction for Time between direct vs. indirect interaction and the number of hands used.

The calculated F for the interaction effect for Error (NLError) is 0.000, with a significance of 0.983. We cannot disprove $H0_{Error}$, and we cannot say whether there is a significant interaction for Error between direct vs. indirect interaction and the number of hands used.

We also reconfirm that the number of hands is significant in time (F=14.284, Sig=0.000), but insignificant in error (F=0.672, Sig=0,413), and that Direct vs. Indirect has significant effect on both time (NLTime) and error (NLError), because of the high F values (202.283 & 429.446), and low Sig (0.000 for both).

Statistical Analysis Summary and Conclusions

We find that the following holds true statistically:

- Direct vs. Indirect Interaction ....Significant in both time and error.
- 1-Hand vs. 2-Hands ....Significant in time, but not in error.
- Interaction Effect ....Significant in time, but not in error.

Comparing this to the means within each group, we can state that the following conclusions from the data are significant:

- **Direct vs. Indirect (Time and Error)**: Subjects were faster and more accurate using Indirect Interaction than using Direct Interaction.
- **Number of Hands (Time):** Subjects were slightly faster using one hand than two hands.
- **Number of Hands (Error)**: We assume that the variability in Error is entirely explained by Direct vs. Indirect interaction,. and the number of hands is not significant.