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User Performance Effects of Input/Output Ratio on Indirect Touch Systems

Bachelor's Thesis at the
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I hereby declare that I have created this work completely on my own and used no other sources or tools than the ones listed, and that I have marked any citations accordingly.

Aachen, September 2013
Rene Linden

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Abstract

In this bachelor thesis we investigated user performance effects in indirect multi-touch systems due to changes in control size. We set up an indirect multi-touch system with a control display ratio of 1:1 to answer the question if it is possible to change the control size to a smaller one without affecting the user performance. To answer this question we did five user tests in which the users had to solve steering tasks that were meant to represent rotation, resizing and dragging.

While we created the tasks we found the limitation of tasks getting unsolvable when the control size is being reduced. Therefore, we limited our research question to still solvable tasks.

In four of five user tests was no statistical significant difference in task completion time between the different tested indirect control sizes found, which indicates that for the tested tasks and control sizes user performance effects do not exist or cancel each other out.

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Conventions

Throughout this thesis we use the following conventions:

- All work in this thesis is, if nothing else is stated, done by myself, but because of aesthetic reasons I decided to write everything in first-person plural.
- Because 17 of 20 users were male, we will use ”he” when referring to a single user. Independently of the real gender of this user.
- The whole thesis is written in American English.
- In the introduction we explain control display ratio and how it is calculated in our study. Starting from this point CD means control display ratio, calculated as we described it in the introduction.
- D\C means control display ratio given by 1\CD.
- REML means Restricted Maximum Likelihood and is used to analyze the datasets of all user tests.
- As overshooting is meant that an user moves his cursor further than a targeted object.
- In regards of control and display size means area.

Chapter 1

Introduction

Indirect and direct systems.

There exist two different kind of input settings for a computer system, direct and indirect. A system is called direct if the input control and the output are the same. A typical example is a tablet pc. If the input control is separated from the output, the system is called indirect (Schmidt et al. [2009]). An example would be a monitor controlled by a touchpad.

When creating an indirect system, it is questionable how big the control should be in comparison to the output, because until now, the question, if the control display ratio in indirect multi-touch systems can differ from 1 : 1 without causing significant effect on the users performance, is still open (Voelker et al. [2013]). In this paper we want to answer this question.

Indirect systems are better for long-time working than direct systems.

Most used computer systems, except smartphones, are nowadays indirect, but why is this the case?
This may be, because the normal workplace offers a vertical and horizontal working area, both which are used by indirect systems (Weiss et al. [2010]).
Also indirect systems do not suffer from the two following disadvantages of direct systems: to stick with the example of a tablet pc as a direct system, we can not place the tablet pc in a position where we can work comfortable for a longer time. If the tablet pc is placed in a vertical position like a normal computer monitor, the user has to lift

his arms to reach the tablet pc, which will result in fatigue if the device is used for a long time. The tablet pc could also be placed horizontally on a table, but in this case the user would suffer from neck problems, since he has to look down to see the output. Indirect systems overcome these problems and the users are capable of working for a longer timespan (Voelker et al. [2013]).

The CD of laptops is smaller than 1.00.

An example for a commonly used indirect touch system is a laptop with a touchpad. A lot of people use these systems every day, without having any problems with the fact that the touchpad is much smaller than the output screen. Therefore, the question, if the control display ratio can differ from 1 : 1, seems to be trivial for this kind of system.

A multi-touch system needs an absolute input technique to control multiple cursors at a time.

It seems so, but this does not help us because laptops differ in one specific aspect to the idea of multi-touch system, we got from Voelker et al. [2013]. The laptop touchpad is capable of recognizing multiple touches, still it uses them to control only one input, i.e. one cursor, and sometimes gestures for scrolling or zooming. The multi-touch system we imagine is capable of controlling one cursor for each touch. A laptop and its used techniques are not capable of this, because of the used relative input technique, also called relative mode: on a laptop screen only one cursor exists. If the user moves his finger over the touchpad from left to right, the cursor will move from its current position to the right. If there is more than one cursor it is unclear how to control all of them with this input technique (Arnaut and Greenstein [1985], Forlines et al. [2006]).
Nowadays exist systems which are capable of controlling multiple cursors at the same time with multiple touch input, like tablet pcs. This is mostly possible because of an absolute input technique. With this technique the cursor appears at the exact same position on the screen where a touch is recognized on the control (Arnaut and Greenstein [1985], Forlines et al. [2006]).

We can change the size of control and display independently.

An indirect multi-touch system could therefore look like this: a tablet pc placed horizontally in front of a monitor with the screen output of the tablet pc shown on the monitor. The users can rest their arms on the table and can easily use several fingers as input on the tablet while having their

neck in a comfortable position to look at the output screen (Voelker et al. [2013]).
It is obvious that we can now change the size of control (the tablet pc) and display (the monitor) independent from each other, which raises the question how this affects the user's performance (Voelker et al. [2013]).

We work with a fixed display size and use it as maximum for the control size.

In this work we will keep the size of the display unaltered and change the control size, because we assume that if the control size can be smaller than the display we can use the free space for other things like widgets that improve the user's performance. It would be possible to use different display sizes and even make the control bigger than the display, but this would increase the number of conditions we have to test, which is too much for the scope of this work. So we decided to use a display size that is normally used in work places and furthermore, limit the control size to not be larger than this.

CD is the commonly used abbreviation of the ratio between control size and display size, calculated by the following formula (Accot and Zhai [2001], Casiez et al. [2008]):

$$CD = \frac{Size\ of\ Control}{Size\ of\ Display}$$

Sometimes, the CD is calculated by dividing the display size by the control size and therefore, is called D/C (Becker and Greenstein [1986], Arnaut and Greenstein [1986, 1987, 1990]). This would mean that the CD would increase when decreasing the control size which we did not find practical.

What happens if the control size is made smaller?

At this point, we already explained what an indirect multitouch system is and how the absolute cursor positioning works, but what are problems and opportunities in downsizing the control? To understand this we want to explain the two main effects of making the control smaller.

The different cursor accelerations could be positive or negative.

The first effect is caused by the different cursor accelerations: if the CD is 1.00 every movement on the control will result in a cursor movement with the same distance on the display. If we now change the CD to 0.25, every movement

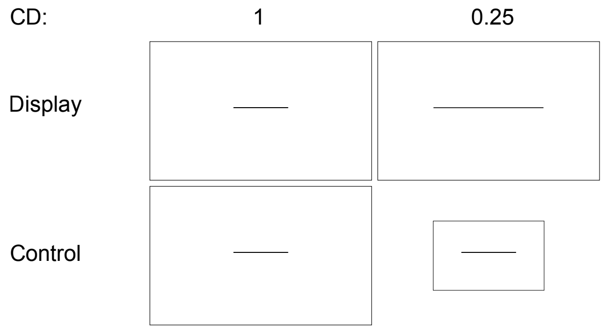

Figure 1.1: Example for cursor acceleration due to CD change. The control movement stays the same, but the cursor movement on the display changes due to the CD change.

on the control will have the doubled distance on the display (Accot and Zhai [2001], Buck [1980]). This effect is illustrated in Figure 1.1.
This can be positive, because the user has to move his hand less far, but it can also be negative, if very fine cursor movement is required. In topic of relative mode, Arnaut and Greenstein [1990] reported, that low CD improves gross movement and that high CD results in better fine movement.

Second effect: shrinking of object control size can lead to problems.

The second effect is the shrinking of the object control size. While the size of objects on the screen stays the same, the size on the control shrinks with the control size. For example at a CD of 1.00, the user has to press a button with a size of 10 x 10 mm on the screen, which is the same area he needs to press on the control. But if the CD is 0.25, the area to press on the control shrinks with the control size to 5 x 5 mm. If the user has to hit certain objects or steer through some menus, this can get very hard and may lead to problems and frustration (Accot and Zhai [2001], Buck [1980]). The factors from the display size to the required control movement for our chosen CDs can be seen in Table 1.1.

CD:	direct	1.00	0.75	0.50	0.25
Display	x	x	x	x	x
Control	x	x	$x * \sqrt{0.75}$	$x * \sqrt{0.5}$	$x * 0.5$

Table 1.1: Display length to control length.

The absolute control size has an effect on the used muscle regions.

It is obvious that the usability of such an indirect multi-touch system does not only depends on the CD but also on the absolute control size (Arnaut and Greenstein [1990]). If the control size is too small to put all the required fingers on it, the user will fail at every CD. Vice versa, if the control size is larger than the area the user can reach with his arm, he will also fail. The control size should possibly be between these two boundaries (Accot and Zhai [2001]).
By choosing a size in between these boundaries another effect arises: the user needs different muscle regions to fulfill the same task. At big control sizes the user needs to use his arm muscles while at smaller ones he can perform more tasks with his fingers and wrist. Accot and Zhai [2001] suggested that this effect influences the user performance, since the muscles preciseness changes with their size.

It is not clear how all these effects interact and if the user performance will be affected significantly, therefore the question remains if we can shrink the CD without significant performance effects on the user.

Some research is done in this area, which we will summarize in the next chapter.

Chapter 2

Related Work

At first, we revised a large amount of literature to figure out if similar questions were already addressed. We searched in different device areas: mouse, direct touch, indirect touch, digitizer pen, joystick, wall sized displays etc., but we did not find results that could be used or transferred to answer our research question. Therefore, we decided to perform an own user study to give an answer to our research question. Nevertheless, we want to show some interesting results in this chapter.

Most related work can not be transferred, due to different input controls.

2.1 Mouse

In the context of mouse and touchpads, which are used in relative mode, CD often means cursor gain or control display gain and not ratio. Since, there is not the actual size of the control changed, the only change will be in the speed of the cursor (Casiez et al. [2008]).

Not all work has the same definition of CD.

Mouses are often evaluated since they are widely used and have existed for decades. Jellinek and Card [1990] showed, that the user is capable of working with high gains, which indicates that a user could also be capable of working with higher cursor gains on indirect touch pads.
This results give no answer to our research question, but

Mouses are too different to tranfer the CD results.

Jellinek and Card [1990] presented an interesting idea by suggesting that the CD should not matter in the user's performance in tapping tasks. Since, the widely used and accepted Fitt's Law does not include any term that is affected by CD.

2.2 Touch Systems

As we already mentioned in the introduction, the question about the CD in relative modes is partially answered, but can not be transferred.
Still it is interesting that users can work with different sized touchpads and cursor gain settings.

Absolute was better than relative mapping and should be used with a D/C of 0.875.

We focused on indirect touch used in absolute mode since it fits our system better than the relative mode. We found some papers on absolute multi-touch systems regarding CD by Arnaut and Greenstein [1985, 1986, 1987, 1990]. They used a system much smaller than our, but with the same setup: indirect touch used in absolute and relative mode, but not capable of multi-touch.
It was investigated how the CD affects the user in selection tasks. They found that a D/C of 0.875, which is a CD about 1.14, used in absolute mode is optimal.

To avoid redundant results, we focus on tasks that require constant finger contact with the touch surface.

The authors mentioned the possibility that the absolute was superior to the relative, because the users lifted their finger from the screen and jumped to the point where they had to select the object. Since it is likely, that the user will do this in normal interaction with absolute systems. This is a valid result, but it also raises the question if this result is different when we have an constant contact of the finger with the touch surface.
When selecting objects by jumping to the position the most difficult task for the user may be to compensate the size difference of the control to the screen, which includes the shrinking of the objects, but avoids the effect of cursor acceleration.
The result of a CD around 1.14, where the display is larger than the control, indicates that in selection tasks the effect of object control size is bigger than the effect of the user performing a bigger movement.

First, their work and results are the reason why we focused on tasks that require constant contact of the finger with the touch surface and second, was their system not capable of any multi-touch, why we included it in our study.

A generalizable definition of CD was not found.

Arnaut and Greenstein [1986] tried to validate the generalizability of two definitions of CD. They did this, because it is not possible to compare results in effects of cursor gain, since the cursor gain does not describe the absolute size of the display or control. They concluded that both were not generalizable.
They also concluded, that lower gains aid target selection, but this effect is limited, since the benefit in fine adjustment is outweighed by the negative effect on gross movement.

Control size, display size, control target width and display target width interact with each other and influence the user performance.

Arnaut and Greenstein [1987] reached some interesting results: there seems to be an effect in user performance which is caused by the interaction of "Control Amplitude x Display Amplitude x Display Target Width". They stated that control and display amplitude are interdependent and the size of the target can change their interaction.
With these result they discussed, that it is "an inadequate specification for performance if three of the four control-display components are independently specified" and sum up that "optimization of a control-display interface must involve specification of at least three of the four design parameters of control amplitude, control target width, display amplitude, and display target width".
Three years later they supported this results, Arnaut and Greenstein [1990].

2.3 Effect of Display Size

The size of the output has an effect on the user.

The fact that the display size has an effect on the user performance is shown in Sutter et al. [2008] and is one reason why we worked with a fixed display size. By fixing the display size and the display target width we focused on the effects of the changes in control size.
Sutter et al. [2008] tested if the motor memory has effects on the human performance. They used an indirect touch system similar to ours and covered the user's view on the con-

trol, so he could not see his movements. They let them perform a simple tapping task and changed the display output. While changing the output the control remained the same. While doing the same task users reported that they believed that their movement had changed. Different task completion times suggest that the size of the output has an effect on the user.

2.4 Digitizer Pen

Changes in CD while using stylus resulted in an inverted U-shaped performance curve.

Another input control that uses absolute input is the stylus or digitizer pen. Accot and Zhai [2001] explained that researchers would think that CD is a well documented topic in HCI, but the results are scattered and controversial.
They used steering tasks to investigate the effects of CD while working with a stylus. They found out that the CD matters and the users had an inverted U-shaped performance curve.
Accot and Zhai [2001] even stated that it is obvious that if we push the question about the effect to extrema it has to have an effect.
This can be transferred to our question, but the rest of the results can still not be transferred since the stylus requires another input gesture than touch does, but it is a good indication for how our results could look like.
Also, we took the idea of using steering tasks in our user study from this work, since it gives a good task design to measure the user performance for tasks that require constant finger contact of the user with the touch surface.

2.5 Wall Sized Displays

Wall sized systems have a much smaller CD than we target for.

Another field of research is working with very small CDs: the control of wall sized displays. Since their display areas are as big as a whole wall, their input devices are very small in comparison. This is possible since they use specific software tools that help the user overcome these extreme CDs. For example McCallum and Irani [2009] use ARC - Pad, an combination of relative and absolute positioning. Abednego et al. [2009] help with their I-Grabber, which grabs objects that are far away. These techniques are meant for single ”cursor” interaction and not for multi-touch from a single user like we focus on. The work on this topic did therefore not have transferable results for us.

2.6 Additional Work

Casiez et al. [2008] tested the user performance with constant gain and in pointing tasks. They compared earlier work on the topic of CD and resulted, that the effect of CD is not yet identified and the results are very controversial. They conclude, that low levels of D/C gain has an negative effect on performance and higher gains increase the overshooting, which indicates an issue with the muscle control accuracy.

Casiez et. al support our findings in related work.

Not on topic of CD but still relevant is the work of Voelker et al. [2013] since they used the same system as we did and delivered the needed framework to create our user tests, which we will describe later on.

Voelker et al. used the same system.

Chapter 3

Performance Test

After looking at related work our initial question is still unanswered: can the control display ratio in indirect multi-touch systems differ from 1 : 1 without significant effect on the user performance?
In the introduction, we limited ourselves to work with a fixed display size and only change the control size, with the biggest size equal to the display, which changes the question to: can the CD in indirect multi-touch systems be smaller than 1.00 without significant effect on the user performance?

We change the research question to fit our limitations.

3.1 Used Device

The used device was given to us by Voelker et al. [2013] and can be seen in Figure 3.1. Therefore, we describe the same system.
The users sat down in front of a self made desk. There were two displays, one horizontally placed in the table and one vertically like a monitor. Each display had the same display area (597 x 336 mm) and resolution (2560 x 1440 pixel). The horizontal display was a capacitive touch-sensing 27″ Perceptive Pixel display. It was embedded in the desk and ran with an effective touch frame rate of 105 Hz. The vertical display was placed about 61 cm in front of the edge

We used two screens, each with a resolution of 2560 x 1440 pixel.

Figure 3.1: The used indirect multi-touch system for our user tests.

of the table and has its bottom-most pixel 13 cm above the desk surface. The display area was about 47 cm apart from the bottom-most pixel of the touch sensing area used in the horizontal touchscreen.

Cardboard frames were used to reduce the control size.

In all tests the participant used the horizontal display for input and saw the task on the vertical screen, except in the direct setting were the output was seen on the horizontal screen. In all settings we placed a frame on the horizontal screen to give a physical and optical feedback about the active area of the touchscreen. This can be seen as example for the CD of 0.50 in Figure 3.2. To exchange them easily they were hold by two screw clamps, seen in Figure 3.1. The frames were made out of 2 mm thick gray cardboard.

Used cursors with diameter of 2.33 mm and an absolute mapping.

The cursors were circular with a constant diameter of ca. 2.33 mm (10 px). Depending on the task there could be one or two cursors at the same time, additional touch sensing was ignored. They were visualized with an absolute mapping of the centroid of the touch contact area to the center of the cursor. The mapping was always absolute, even with a shrunk control, which was realized by the software, by recalculating the position from the smaller control to the bigger screen. We chose 1.00, 0.75, 0.50 and 0.25 as the tested

Figure 3.2: Used device with frame for CD of 0.50

control sizes. 0.25 was chosen as smallest CD because at that size the whole surface could nearly be covered using both hands. Also, we added a direct setting as comparison. Direct is more natural than indirect and we assumed that it is faster (Schmidt et al. [2009], Forlines et al. [2007]). If a different between the indirect settings exists, direct will serve as compare value of the size of the effect.

3.2 Software

Simon Voelker provided us with a helpful framework.

The software for the user study was written in Objective C. The used IDE was XCode at version 4.6.2. The used version control system was Git in combination with the GUI Tower. The data analysis was done with JMP 10.0.2. Simon Voelker provided us with his framework TableEngine. This framework included the functionality to draw geometries on the screen and to receive the

touch events. Furthermore, he supplied us the Multi Screen Agent that switch the output between different screens, which was used to switch to direct setting (Voelker [2010]). It also allowed us to use an iPad for testing.
Our own work was to design and implement the user study.

3.3 Implementation

We first generated all trials and then used an executer to control the user tests.

The trial classes included the logic of each user test.

We had to complete several tasks in our implementation. First, we needed to generate and order the tasks. With the user ID as input we generated them and used a hard coded latinsquare to set them in the correct order. A trial executer then executed one trial after another. Each user test had its own trial class. These classes implemented the same interface to fit in our executer. Each trial type had to draw its components, generate one raw data logger and handle the users input. The input was given to the trials by a touch handler. This handler did draw a cursor at each point of a touch event and deletes the ones which were too much or not present anymore. Also, it recalculated the position in smaller CDs. The whole touchscreen was still sensing touches in smaller CDs, but only those in the active area were processed. Therefore we recalculated the position before drawing the cursor and informing the trial. Therefore, the trial worked exactly the same in all CDs. After starting a trial the executer waits until it gets the information that the trial was successful. In this case it erases all objects to make sure that no side effects appear and starts the next trial or shows some between screens.

3.4 Pre Findings

There are tasks which can be solved at a CD of 1.00, but not at 0.25 and vice versa.

We observed some interesting facts for our research question while implementing the software of the user study: a task that can be solved in a CD of 1.00 can be unsolvable in 0.25 and vice versa.
This is because of the touch characteristics. The center

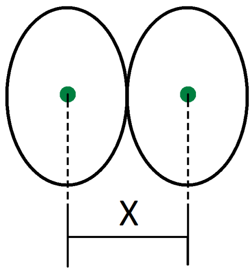

Figure 3.3: The smallest possible distance of two touches. Two touches caused by fingers can never be at the same position while using our touch to cursor mapping.

points of two touches will never be at the same position. We illustrated this in Figure 3.3.

Therefore two cursors can not be at the same position, since we are using the center points of the touched to calculate the cursor positions. In a CD of 1.00 the distance is x, but with smaller CDs it increases, this can be seen in Table 3.1.

CD:	direct	1.00	0.75	0.5	0.25
Control	x	x	x	x	x
Display	x	x	$x * \sqrt{\frac{4}{3}}$	$x * \sqrt{2}$	$x * 2$

Table 3.1: Control distance to display distance.

If the task is to position the cursors into a circle with the diameter of x + 1 pixel, it is solvable at a CD of 1.00, in opposite, it gets unsolvable at smaller CDs (as long as $x \geq 1$, which is true for most touch inputs).

Small CDs can make tasks sovable, which are unsovable at higher CDs.

Also, we found out that a task can be solvable at a CD of 0.25, but not at a CD of 1.00. If the user has to use two fingers of the same hand, his ability to move both cursors apart from each other is limited by the span of this fingers. In the case, that this maximum distance on the control is y, we can see in our Table 3.1 that this distance on the screen increases as the CD shrinks. A task, that requires to move two cursors y + 1 pixel apart from each other, can be accomplished at CDs that are smaller than 1.00 but not at 1.00 itself (as long as $x \geq 1$).

3.4.1 Pre Limitation and Result

Considering all types of tasks our research question can be denied.

We found a limitation of our research question: the question if the CD can be smaller than 1.00 can only be answered depending on the tasks the users have to perform. Using a smaller CD in combination with multiple cursors increases the risk, that the user can not solve a task, since the fingers can not be moved close enough together to position the cursors correctly.
Considering systems on which such tasks have to be performed and no helping hardware or software tools are included to overcome this problem, we can answer our research question with:

No, the CD can not be smaller than 1.00, because it is possible that the users get stuck and frustrated since they can not solve given tasks with the system.

We limit our work to tasks that are solvable on all tested CDs.

The second finding, that smaller CD make it possible to fulfill tasks, shows us that smaller CDs can be useful. For our further work, we want to focus on tasks that can be solved at any tested CD. All kind of single touch tasks and multi-touch tasks which not suffer from this limitation.

3.4.2 Pre Study

Voluntary testers helped finding the best sizes for the different task types.

Since we decided to use direct, 1.00, 0.75, 0.50 and 0.25 as our conditions for CD, we had to find sizes for the tasks, which are challenging through all of them and are still solvable. To identify them, we set up a small pre study, including six different user tests with a limited amount of testers and trials.
Three people, one female and two males, picked randomly from the chair and without being payed, were asked to solve each task of each user test with different sizes. These sizes were set by us with the goal to be most challenging.

The testers were encouraged to tell us about their problems while solving the tasks. The smallest size, that can be solved without major problems, were chosen for the final test set up. The exact values will be mentioned in the user test description.

After this, we finished the implementation and performed another pre study with one user, who had to do all tests to determine the time for the tests and to give feedback about possible friction and fatigue.
As we expected, he needed about one hour. He reported that in the end he suffered from extensive friction, so we excluded one test and were left with five, which we will present later on.
Also, the user did not always realize that the input method changed, because he was too focused on the task and so did not recognize the text telling him that the input type had changed. So we included the type screens for the final test, which we will explain later in this thesis.

One tester did the whole study earlier to determine how long it will take.

3.5 Participants

20 people participated in our tests, all were volunteers. They were between 20 and 31 years old and the average age was 24.05. Three participants were female and 17 male. All participants were right handed.
We offered beverages and candy. 15 users are studying or studied computer science or computer science related courses. Three participants are studying technical communication, one studies business administration and one is a physiotherapist.

20 people participated in all five tests.

3.6 Test Conditions

3.6.1 Introduction of the User

All participants had the procedure explained.

Each participant got the same independent explanation of the procedure, like described in the following.
At the beginning, the participant was asked to carefully read the consent form A.1 and sign it. The form included the common information about approximate taken time, risks and the procedure. Afterward, he was asked to fill out the top part of the questionaire B.1 with his age, gender and occupation. Then, he was asked to sit comfortable in front of the system and the introduction started. Additionally, we provided complimentary snacks and non-alcoholic drinks.

There were five control size screens.

First, we explained and showed that there will be five screens, one for each CD condition, which looked like the one in Figure 3.4. At this moment, we had to change the frame and the participant had the opportunity to have a break and take some snacks or drinks. Additionally, he was allowed to rest at any point during the study. Then, we asked him to use the system to press the continue button which was shown on the control size screen.

Before each task an information about the used fingers was shown.

The next screen showed up, looking like the screen in Figure 3.5, and the user was told that there will be three different of them, telling him to use one finger, two fingers or both hands. One of these was shown before each new task. Again, we asked him to press the continue field.

After each input information two trainings were done.

After he did press the continue button, a training session for the task was shown. There were two for each task and they did not differ from normal sessions except for a text at the top of the screen which stated that this was training and which condition the user should use. A sample training session can be seen in Figure 3.6

Then the ten measured trials started.

The seen task was explained and he was informed that these training sessions were not measured. The measured tasks were those without the training label. We explained him that if he had comments, problems or needed help at

Figure 3.4: One of the screens shown every time the CD changes.

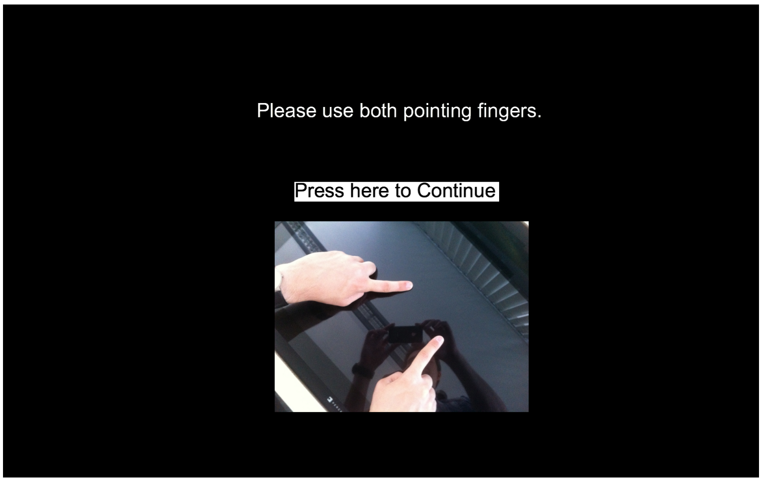

Figure 3.5: One of the screens shown before every training session.

any point, he could tell us so. The whole time, we were sitting next to him. Also, we encouraged him to take breaks at any point he want to, except while he was doing a measured trial. If we observed any behavior of the user which indicates fatigue, like relaxing his hand, we asked him to take a break. After that the user was allowed to start with the test.

Figure 3.6: This is a sample test session.

For user test 3 we had to tell the user how to place his fingers.

When the task for user test 3 appeared, we told him to put his right finger into the top area and the left in the bottom, if he did not do this by himself. It was controlled, that in all other tests the same finger positioning was done by all users. Nevertheless, this seemed to be obvious to the user, since nobody showed varied behavior.

After finishing a "thank you" - screen appeared, seen in Figure 3.7 and the user was asked for any additional comments about the test.

3.6.2 Mixed Order of User Tests

There were five user tests, each consisting of fulfilling one steering task in all five control size settings: 0.25, 0.50, 0.75, 1.00 and direct.

- **User test 1** - drag with right pointing finger
- **User test 2** - rotate with right pointing finger and thumb
- **User test 3** - rotate with both pointing fingers

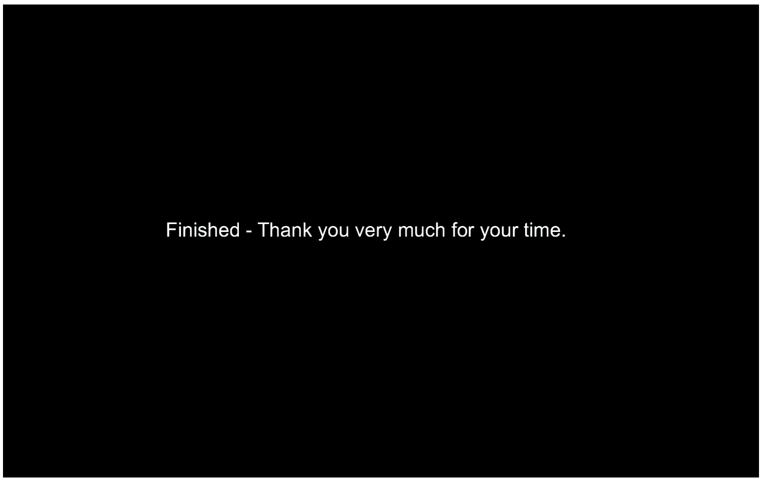

Figure 3.7: Thank you screen shown at the end of the tests.

- **User test 4** - resize with right pointing finger and thumb
- **User test 5** - resize with both pointing fingers

To avoid the changing of the CD frame after each task, each user did all five tests for one control size and then switches to the next. This should also help to avoid a bored user. The order of the control sizes was counterbalanced by a latinsquare.

Counterbalanced CD by latinsquare.

The order of the tests in a condition was also randomized by a latinsquare. Which order was chosen depended on the control size and the user id. Every user did all five orders of tests found in the latinsquare, one for each control size. Which order was used for which control size was determined by calculating the following formula:

Mixed Studies into another.

$$(Number\ of\ User\ Test + User\ ID)\ mod\ 5$$

Before each user test in each control size the user had two training and after these ten measured trials. This results in 5 control sizes $*$ 10 trials $*$ 5 tasks = 250 measured trials (plus 5 control sizes $*$ 2 trainings $*$ 5 tasks = 50 training trials) and

This work has an overall count of 5000 measured trials.

took about 60 minutes. Resulting in 5000 measured trials for all 20 users, divided by the count of user tests every test had 1000 measured trials, 200 for each condition.
In the result analysis, the completion time of each user for a CD in a user test was defined to be the mean of his time delta of all 10 his trials for that specific user test and CD. Therefore, the count of data points used in the data analysis is divided by 10. The time delta will be explained in the following chapter.
Each of the additional data analysis include 2000 measured trials, because they combine two of the previous tests.

3.7 Measurements

All touch events were logged to be able to reproduce the study.

To make it possible to reproduce our study we logged all data about touch events in one file for each trial of every user. This file included all attributes of all recognized touches.
Additionally, we logged one file for each user with a line for each trial. Each line had the data for one trial including the following values:

- *user ID*
- *trial count* - position number of the trial
- *control size*
- *task Type*
- *start time* - time point when first touch entered steering area
- *end time* - time point when last touch left steering area
- *time delta* - end time minus start time
- *retries* - how often the user had to redo the trial until he finished it (includes loses and lefts of all touches)

For each touch we measured some additional values. Except the loses and lefts all were measured for the succeeded trial and were not depending on the retries.

- *touch ID* - the ID of the touch that was used to fulfill the task
- *touch count* - the count of touch events of this touch
- *standard deviation* - calculated standard deviation from the middle line of the steering area to the actual moved path
- *touch start time* - time point when the touch entered the steering area
- *touch end time* - time point when the touch left the steering area
- *time delta* - touch end time minus touch start time
- *touch loses* - count of retries, that were causes by losing the touch
- *touch lefts* - count of retries, that were causes by this touch leaving the steering area in wrong direction
- *distance* - the moved distance during the measured time period

3.8 User Study

For our user study we took three tasks that represent the touch interactions: dragging, rotating and resizing. Resizing and rotating is done with one and two hands, which results in five different interactions we test, divided in five user tests we describe in the following sections.

The user studies were designed to represent common touch interactions.

The datasets we received were all normally distributed. Therefore, we could use the Restricted Maximum Likelihood (REML) method to analyze the data.

3.8.1 User Test 1

The first test represents a dragging task. With this we investigated the user performance in single finger interaction for different control sizes.

As performance measurement we took the completion time of the successful trial. We hypothesized the following outcome:

- **H_1:** None of the indirect control sizes has a significant difference in completion time to another indirect control size.
- **H_2:** The direct interaction has a significant smaller completion time than all indirect settings.

We hypothesized $\mathbf{H}_1$, because we have no explicit reason to believe, that a specific CD is better than others or that any of the mentioned effects, that occur when reducing the control size, is stronger than another.

$\mathbf{H}_2$ was hypothesized, because the direct setting is stated to be more natural and therefore, may be faster than the indirect setting (Schmidt et al. [2009], Forlines et al. [2007]).

Experimental Design

This task is already described in Accot and Zhai [2001]. The task consists of a starting area (green) and a steering area (gray), seen in Figure 3.8.

To fulfill the task the user had to move the cursor into the starting area and steer through the steering area out to the end without leaving the area in any other direction. The user had to perform this task for every CD which is the independent variable.

The object size on the control depend on the CD.

The starting area was square with the side length of the height of the steering area. The steering area was 1500 pixel (about 349.8 mm) long and 40 pixel high (about 9.33 mm) on the screen.
This was the same for all CDs, but the movement the user had to perform on the touch screen to fulfill the task was depending on the CD and therefore, had the values found in Table 3.2. The bottom left pixel of the starting area was

Figure 3.8: Task type 1 - one finger straight. Task type represents dragging. The starting area is green and the steering area gray.

about 512 pixel away of the left side and 750 pixel above the bottom side of the screen.

	Width		Height	
CD	px	mm	px	mm
direct	1500	349.8	40	9.33
1.00	1500	349.8	40	9.33
0.75	1299.04	302.94	34.64	8.08
0.50	1060.66	247.35	28.28	6.6
0.25	750	174.90	20	4.66

Table 3.2: Sizes of steering area on the control of **task type 1**. All mm values and the px values of 0.75 and 0.50 are approximate.

The user did two training and ten measured trials for each control size, which resulted in 60 trials. We recorded the following dependent variable to verify our hypotheses:

- **Completion time** - mean of time delta for the 10 successful trials of a user

Method

For each trial the starting and steering area were shown. The steering area stayed gray until the user placed his finger in the starting area, then it turned blue after a short delay of 0.5 to 2.0 seconds to inform the user, that the task can be started, this can be seen in Figure 3.9. The delay was included to avoid that the user overshoots the starting area

After placing a touch in the starting area, the steering area turned blue.

Figure 3.9: Task Type 1 - task is ready to start.

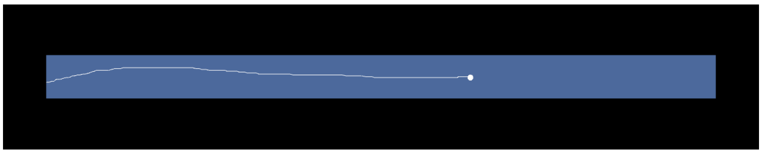

Figure 3.10: Task Type 1 - user started the task.

and run into the steering area, starting the task unintentionally.

The measurments were not affected before the acutal task started.

If the user left the starting area into an other direction than the steering area or if he lifts his finger, the steering area would turn gray and the system waits for the user to put his finger into the starting area again. In this case, no measurement would have been started.
The hardware can recognize more than one touch, but only one is shown at a time. All not shown touches have no effect on the task. This allowed the user to rest his arms or other fingers on the surface without influencing the study.

Going from start into steering area starts the trial.

As soon as the user leaves the starting area into the steering area, the actual task starts. This moment is the point where the measurement starts. With the start of the task the touch starts drawing a thin white line, representing the path of the touch, as shown in Figure 3.10. Furthermore, the starting area disappears, indicating that the task started and the user can not return.

The user is not allowed to leave the steering area.

Then the user has to move his finger through the steering area. If he leaves the area in any direction different than the end or if he lifts his finger, the trial will be stopped and restarted. Only if the user reaches the end of the steering area and leaves it to the right side, the task is fulfilled. As a feedback to the user the screen turned green for 0.1 seconds.

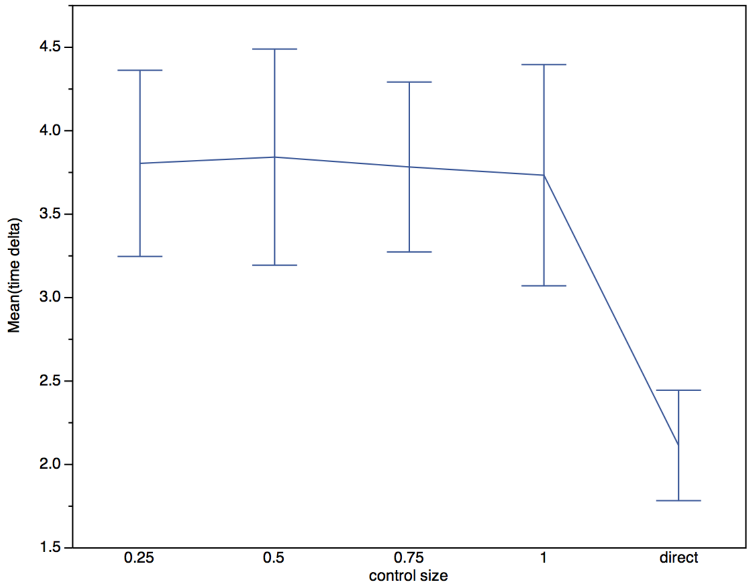

Figure 3.11: User Test 1 - the mean of time delta with a confidence interval of 95%.

Results

Direct was significant faster than all indirect settings.

We used the REML method with user as random effect and control size as effect to analyze the dataset. The result shows a significant effect of control size ($F(76) = 21.2047$; $p < 0.0001$).

A pairwise comparison of CDs shows that the direct setting is significant faster than all indirect settings, while all indirect settings show no significant difference. Detailed results of the pairwise comparison can be found in Table 3.3. Therefore, we can conclude that the $\mathbf{H}_1$ did hold, because none of the indirect settings was significant faster or slower than the other. Also did $\mathbf{H}_2$ hold. Direct interaction is significant faster than all indirect settings.

Direct 44% faster than indirect.

To determine the effect size we grouped all indirect settings, since they have no statistical difference, and calculated the difference between the means of the indirect and direct setting. Additionally we calculated Cohen's d between indirect and direct. All results can be found

	t(76)=	p
direct vs 1.00	7.02298	<0.001
direct vs 0.75	7.236838	<0.001
direct vs 0.50	7.493227	<0.001
direct vs 0.25	7.330874	<0.001
1.00 vs 0.75	-0.21386	1
1.00 vs 0.50	-0.47025	1
1.00 vs 0.25	-0.30789	1
0.75 vs 0.50	-0.25639	1
0.75 vs 0.25	-0.09404	1
0.50 vs 0.25	0.162353	1

Table 3.3: User test 1 - results of pairwise Student's t test after Bonferroni post hoc correction to fit in the confidence interval of 95%.

in Table 3.4. Since the direct mean was about 2.1142191 seconds. This means that direct was about 44% faster than indirect.

	difference in means	Cohen's d
direct vs indirect	1.6764543	1.849053659

Table 3.4: User test 1 - effect size calculated by difference in means and Cohen's d.

Discussion

The input technique is probably the only factor that could affect the user performance.

In comparison to all indirect settings did the direct setting result in a significantly better user performance. Since we tried to exclude most effects that could affect the result due to our study design, the result should only be generated by the input technique (direct or indirect) or the different control sizes. It is unlikely that the control size has had an effect on the comparison of direct vs indirect, because the control size is the same in indirect 1.00 and direct. Also, no significant effect could be found in any of the indirect settings in comparison to other indirect CDs.

Therefore, the reason of the performance difference seems to be the direct interaction. This is not surprising, because the direct interaction is more native and the user does not need to compensate the indirect control of the cursor by cognitive work (Schmidt et al. [2009], Forlines et al. [2007]). So we could assume that the direct interaction is better for this kind of task, but the following observation does lower the quality of the result.

We can not conclude that the direct interaction improves the user performance.

Due to this simple task most users were able to move their finger very fast, which resulted in some latency of the cursor. This latency was caused by the system itself and therefore, could not be avoided by our software. In direct setting of this task it resulted in a big improvement to the user, since the cursor was slower than the actual finger, the user did not have the disadvantage of direct interaction, that he covered important parts of the output.

Thus we can assume that at least the effect size of this task is affected by this latency and is not precise. In other tasks the user moved much slower, which made this effect not visible.

If we compare the indirect settings, we can not find a significant effect on the completion time of the task. We could have expected an effect since Accot and Zhai [2001] reported an effect which was probably caused by the use of different muscle regions. We changed the size of the control enough to hopefully see this result too, but the data does not show the reported effect.

Expected results of other studies did not appear.

Another reason to expect an effect is the result of Arnaut and Greenstein [1985], who found evidence for an effect in indirect tapping tasks. We assume, that our decision in related work was correct, that both devices and interactions are not similar enough to ours to transfer the results.

We could also have assumed, that in straight one finger dragging tasks, which seem to be fairly easy, the cursor acceleration reduces the completion time, but it seems that the smaller control objective size compensate the speed improvement.

3.8.2 User Test 2

User test 2 represents an one hand rotation.

This user test represents a rotation done with one hand using the thumb and the pointing finger. Therefore, it is a multi-touch test, unlike user test 1. We investigated the user performance in rotation tasks in different CDs with this study.

The measurements and the hypotheses stayed the same as in user test 1.

Experimental Design

The task consists of a two starting areas and two steering areas, seen in Figure 3.12.

To fulfill the task the user had to move one cursor in each starting area and steer with each through the bordering steering area out to the end without leaving the area in any other direction.

Both steering and starting areas where of the same size.

The user had to perform this task for every CD which is like before the independent variable. The starting areas were squares with the side lengths of the height of the steering areas. The steering areas were each 400 pixel (about 93.28 mm) long and 50 pixel high (about 11.66 mm) on the screen. Like before, this stayed the same for all CDs, but the movement the user had to perform on the touch screen to fulfill the task was depending on the CD and therefore, had the values found in Table 3.5. These areas were generated around the middle of the screen. The bottom left corner of the steering area was about 255 pixel apart from the middle of the screen.

The count of trials and the dependent variable stayed the same as in user test 1.

Figure 3.12: Task Type 2 - two finger task representing rotation

Method

The final task can be seen in Figure 3.12, to reach this we did a large amount of prototypes. The first task design was a 180 degree rotation with starting areas aligned horizontally to each other. The next was 180 with vertical starting positions, followed by 90 degree horizontal and 90 degree vertical.

Many versions of the rotation task were implemented and tested.

We took ourselves and other people of the chair to test the task and most people mentioned that this task could not be completed in a comfortable way. We identified a certain area that was always reported to be an uncomfortable hand posture if the user had to rotate clockwise through this area, marked in 3.13. To avoid this area our final version is rotated by 45 degree, seen in Figure 3.12.

	Width		Height	
CD	px	mm	px	mm
direct	400	93.28	50	11.66
1.00	400	93.28	50	11.66
0.75	346.42	80.78	43.3	10.1
0.50	282.84	65.96	35.36	8.24
0.25	200	46.64	25	5.83

Table 3.5: Sizes of steering areas on the control of **task type 2**. All mm values and the px values of 0.75 and 0.50 are approximately.

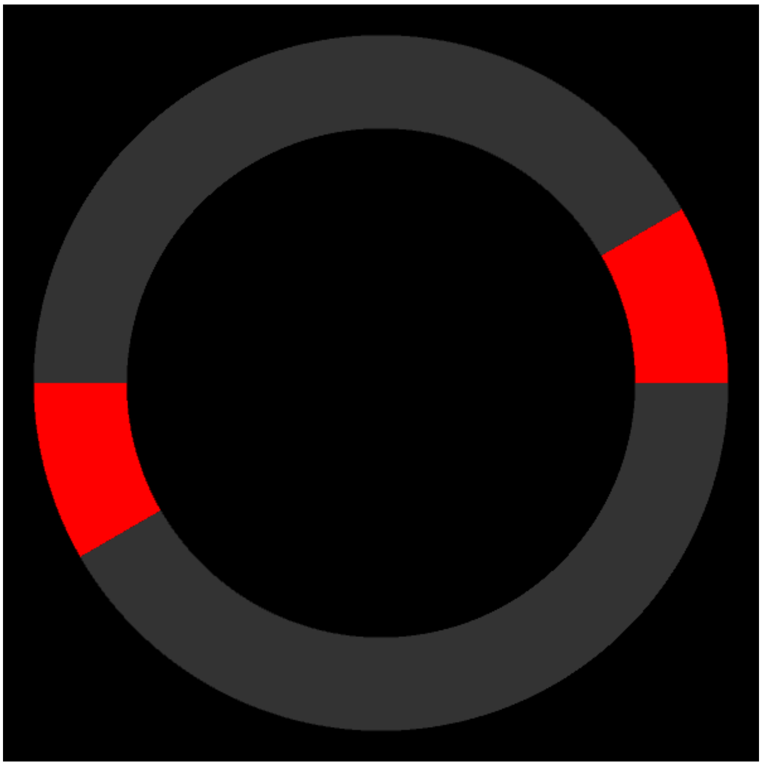

Figure 3.13: Task Type 2 - areas where the task get uncomfortable for the user

The user has to move both cursors into starting areas to start the task.

Like in single touch we filtered all inputs except the two needed touches. Both steering areas stay grayed until the user moves a cursor in each starting area. He had to use the pointing finger to control the top cursor and the thumb to

control the bottom one. While only one touch is in a starting area, leaving or entering, the starting area will not change anything.
If both touches are in different starting areas both steering areas turn blue. If one of the touches leave into another direction than the bordering steering area, the areas will get grayed again.

If one cursor enters the steering area next to the starting area the task is started. That causes that both starting areas disappear, indicating that the task started. The touch which entered the steering area is drawing a white line like the touch in user test 1. The other touch will start drawing a line after he entered its steering area.
Does the other touch not enter the steering area but moves out of the area, where the starting area used to be, in another direction than the steering area, the task is restarted. This restart is similar to a leaving of the steering area to the wrong direction. If one touch is lost or left the steering area, the whole trial is also restarted.

Each cursor starts and stops drawing a line separately.

The task is solved if both touches leave their steering area at the end. If one touch leaves to the end the drawing stops and the drawn line of the touch disappears. The user is then allowed to move the touch free around without influencing the rest of the trial, but he is not allowed to lift his finger. This will still cause an restart. Is the task solved the screen turns green as in user test 1.

To solve the task both cursors have to leave the steering area to the end.

Results

Like in user test one we used the REML method with user as random effect and control size as effect to analyze the dataset. The result shows a significant effect of control size ($F(76) = 23.6414$; $p < 0.0001$).

Direct was significant faster than all indirect settings.

A pairwise comparison of the CDs shows that the direct setting results in a significant difference in comparison to all indirect settings. Detailed results are shown in Table 3.6. $\mathbf{H}_2$ did hold again. The CD of 1.00 is significant faster than 0.25. Therefore, $\mathbf{H}_1$ did not hold.

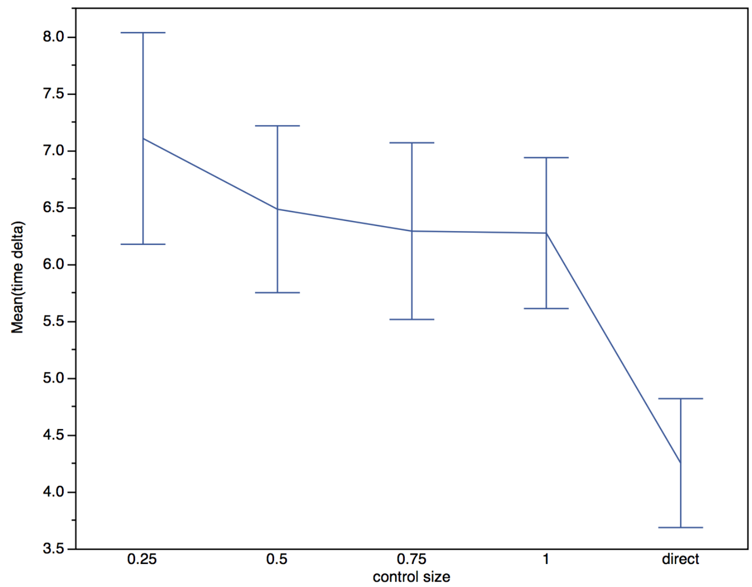

Figure 3.14: User Test 2 - the mean completion time with a confidence interval of 95%.

We compared the means and calculated Cohen's d between direct and each indirect setting to determine the effect sizes Unlike before we not could group all indirect settings. Additionally we calculated these for CD 1.00 vs CD 0.25. All results can be found in Table 3.7.

Direct had a mean completion time of 4.2562529 seconds and therefore, is about 40% faster than the CD of 0.25, about 34% faster than the CD of 0.50, about 32% faster than the CD of 0.75 and about 32% faster than the CD of 1.00. In comparison to this, the effect of 1.00 vs 0.25 was much smaller. The mean completion time of 1.00 was 6.2758856 seconds and therefore, about 12% faster than the CD of 0.25.

Discussion

User reported that in direct interaction they covered the output.

Seven user reported that it was difficult to complete the task in direct interaction since they covered some of the output with their hand, but still the completion time is significantly smaller in direct than in indirect. We assume that

	t(76)=	p
direct vs 1.00	6.455522	<0.001
direct vs 0.75	6.510415	<0.001
direct vs 0.50	7.124502	<0.001
direct vs 0.25	9.110908	<0.001
1.00 vs 0.75	-0.05489	1
1.00 vs 0.50	-0.66898	1
1.00 vs 0.25	-2.65539	0.048
0.75 vs 0.50	-0.61409	1
0.75 vs 0.25	-2.60049	0.056
0.50 vs 0.25	-1.98641	0.253

Table 3.6: User test 2 - results of pairwise Student's t test after Bonferroni post hoc correction to fit in the confidence interval of 95%.

	difference in means	Cohen's d
direct vs 0.25	2.8503795	1.784702608
direct vs 0.50	2.2289256	1.606851804
direct vs 0.75	2.0368061	1.421272813
direct vs 1.00	2.0196327	1.538907827
1.00 vs 0.25	0.8307468	0.488583769

Table 3.7: User test 2 - effect size calculated due to difference in means and Cohen's d.

this is caused by the more direct interaction (Forlines et al. [2007], Schmidt et al. [2009]). As Schmidt et al. [2009] reported, it seems obvious that comparing the own movement with the resulting output on the screen and readjusting the movement, is harder in indirect than in direct, since the control and display are further away from each other in indirect. Additionally, this effect can be increased by the fact that the steering areas were to far away from each other to see both at a time, what was reported by five user as problem.

Therefore, we assume that a direct interaction can be superior in this kind of task.

The effect between indirect settings was much smaller.

Still, there was another significant effect in our data: the completion time in the CD of 1.00 is significant faster than the in the CD of 0.25. This fact lead to rejection of $\mathbf{H}_1$ and indicates that the task gets harder with smaller CDs and therefore, has an effect on the user performance, but it is much smaller than the effect of indirect vs direct, seen at the effect size in Table 3.7.

3.8.3 User Test 3

Represents rotating with two hands.

This user test is representing a rotation done with both pointing fingers. We investigated the user performance in rotation task with both hands for different CDs with this test.

The measurements and the hypotheses stayed the same as in the user test before.

Experimental Design

The experimental design stays the same as in user test 2.

Method

The user was told how to position both pointing fingers.

The method stays the same as in user test 2 except that the user now uses both pointing fingers. He was told to use his right pointing finger to control the top cursor and the left for the bottom area.
This was found out as the preferred way in the pre study and was the setting where the user is pulling and not pushing the finger, which is equal to the other tests.

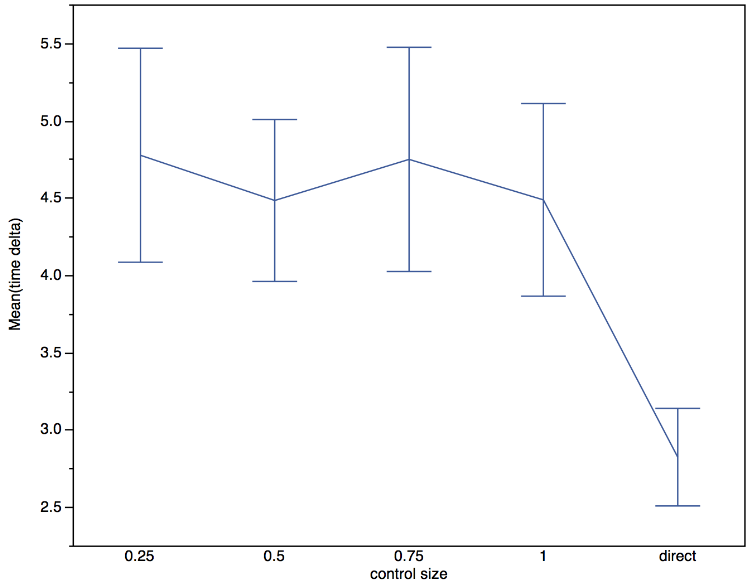

Figure 3.15: User Test 3 - the mean of completion time with a confidence interval of 95%.

Results

The method to analyze the dataset stayed the same as before, REML method with user as random effect and control size as effect. The result shows a significant effect of control size ($F(76) = 14.2604$; $p < 0.0001$).

Direct was significant faster than all indirect settings.

The pairwise comparison of the CDs, which results can be seen in Table 3.8, shows that again the direct setting results in a significant difference in comparison to all indirect settings and none of these indirect settings is significant different to another indirect setting. These results are the reason why $\mathbf{H}_1$ and $\mathbf{H}_2$ did hold.

Like in user test 1 we grouped all indirect settings, since there was no statistical difference between them and compared the means and calculated Cohen's d in comparison to the direct setting to determine the effect size. All results can be found in Table 3.9.

	t(76)=	p
direct vs 1.00	5.437235	<0.001
direct vs 0.75	6.293339	<0.001
direct vs 0.50	5.424685	<0.001
direct vs 0.25	6.380383	<0.001
1.00 vs 0.75	-0.8561	1
1.00 vs 0.50	0.01255	1
1.00 vs 0.25	-0.94315	1
0.75 vs 0.50	0.868654	1
0.75 vs 0.25	-0.08704	1
0.50 vs 0.25	-0.9557	1

Table 3.8: User test 3 - results of pairwise Student's t test after Bonferroni post hoc correction to fit in the confidence interval of 95%.

	difference in Means	Cohen's d
direct vs indirect	1.8006225	2.030292085

Table 3.9: User test 3 - effect size calculated due to difference in means and Cohen's d.

The mean direct completion time was 2.8266013 seconds and therefore, about 39% faster than in the indirect CDs.

Discussion

Users could not see both areas at a time.

Five users complained about not seeing both cursors at a time since the two areas were to far away from each other, which resulted in intuitively not moving both fingers at the same time. One user reported to be a pianist and that he is used to look at two things a time and that he tried to concentrate on the middle of the circle to see both pointers at the same time, but this seemed to be hard.

Direct setting is significant better than all indirect settings. Therefore, $\mathbf{H}_2$ did hold as in user test 1 and 2. Like before, we assume that this may be because of the more native direct interaction (Forlines et al. [2007], Schmidt et al. [2009]).

All indirect settings show no significant difference, which indicates that there is no effect on the user performance or the effects that exist compensate each other between these CDs. This is similar to user test 1 and the reason why $\mathbf{H}_1$ did hold, but this is different to user test 2, where 0.25 is slower than 1.00. The only difference to user test is the input technique of one and two hand. We assume that the task may be easier with two hands than one. To analyze this we will make some additional analysis.

3.8.4 User Test 4

The fourth test represents a resizing task with one hand using the thumb and the pointing finger. We investigated the user performance in resizing tasks with one hand for different CDs with this test.

Represents a resizing interaction with one hand.

The measurements and the hypotheses stayed the same as in the tests before.

Experimental Design

The tasks consists of the same components as the one in user test 2 and 3, but the steering areas are now straight and not rounded. The positioning also different, seen in 3.16.

To fulfill the task the user had to move one cursor in each starting area and steer with each through the steering area out to the end without leaving the area in any other direction.

The user had to perform this task for every CD which is like before the independent variable. The starting areas were squares with the side length of the height of the steering areas. The steering areas were each 150 pixel (about 34.98 mm) long and 30 pixel high (about 7 mm) on the screen.
As before this stayed the same for all CDs, but the movement the user had to perform on the touch screen to fulfill

The size is still dependent of the CD.

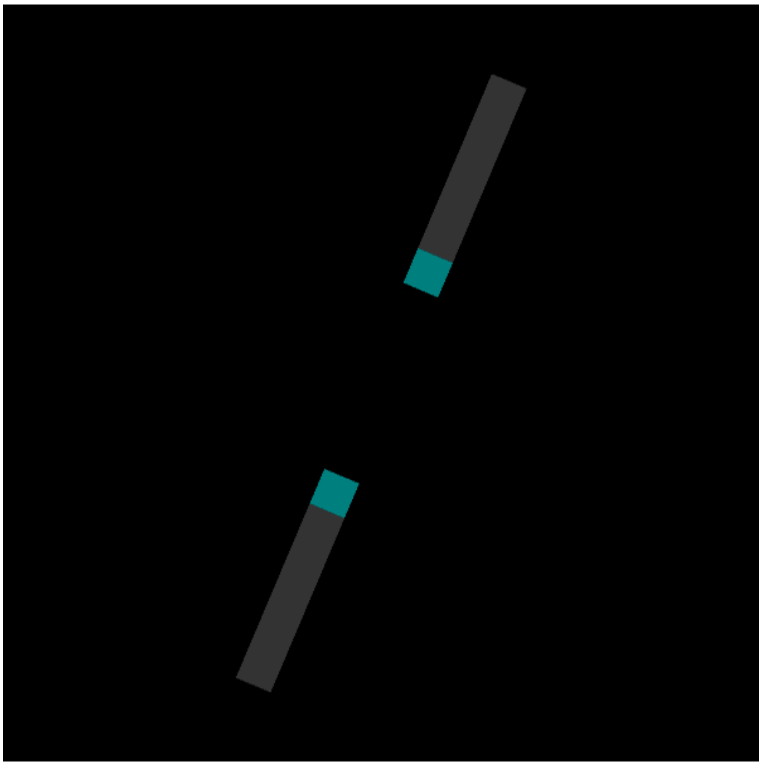

Figure 3.16: Task Type 3 - representing resizing

the task depended on the CD and therefore, had the values found in Table 3.10. These areas were generated around the middle of the screen. The starting areas were 80 pixel apart from the middle of the screen.

The user did two training and ten measured trials for each of the five control sizes, which resulted in 60 trials, like in all user tests.

We recorded the same dependent variable as in user test 2 and 3.

CD	Width px	mm	Height px	mm
direct	150	34.98	30	7
1.00	150	34.98	30	7
0.75	129.9	30.29	25.98	6.06
0.50	106.07	24.73	21.21	4.95
0.25	75	17.49	15	3.5

Table 3.10: Sizes of steering areas on the control of **task type 3**. All mm values and the px values of 0.75 and 0.50 are approximately

Method

The areas are placed in an angle of 67.25 degree.

We designed this task first with steering areas placed in an angle of 45 degree but this was reported as uncomfortable. Therefore, we changed to 67.25 degree what seemed to work better for the users.
The user had to position his pointing finger in the top and his thumb in the bottom starting area.

The behavior of the task stayed the same as the behavior of task type 2.

Results

Direct was significant faster than the indirect CDs 0.50 and 0.25.

The REML method was used with user as random effect and control size as effect to analyze the data. It shows a significant effect of control size ($F(76) = 4.0731$; $p = 0.0048$).

A pairwise comparison of CDs, which detailed results are presented in Table 3.11, shows that the direct setting is significant better than the indirect CD of 0.50 and 0.25. That does mean, that $\mathbf{H}_2$ did not hold, since some indirect CDs are statistically equal to direct.
Since none of the indirect CDs is significant faster or slower in comparison to another indirect CD, $\mathbf{H}_1$ did hold.

Still are two comparisons statistically different to another and therefore, we calculated the effect size. To determine

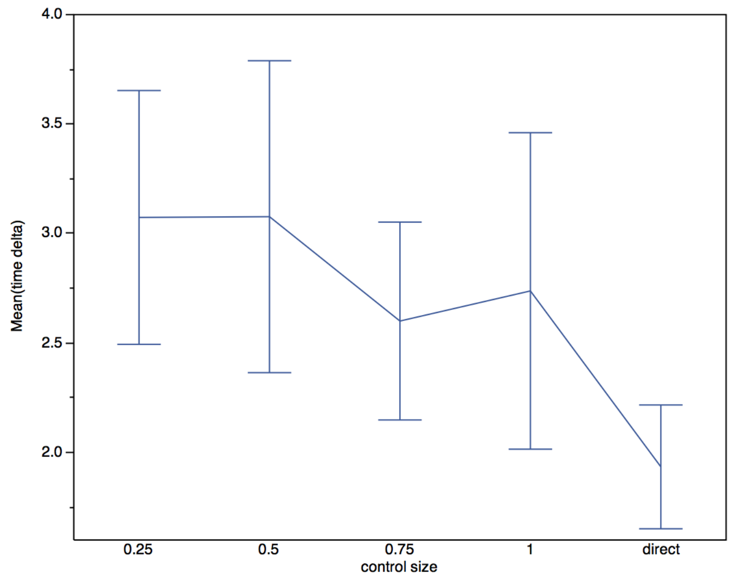

Figure 3.17: User Test 4 - mean completion time with a confidence interval of 95%.

the effect size, we calculated the difference between the mean of the indirect and direct 0.25 and 0.50 setting. Additionally we calculated Cohen's d. All results can be found in Table 3.12.

Since the direct setting had an mean completion time of 1.9340866 seconds it was about 37% faster than the CDs of 0.50 and 0.25.

Discussion

The areas seem to be to small for the users in direct setting.

This user test is the only one, in which direct is not significant faster than all indirect settings. We assume that this is caused by the steering area size. We did observe that most user had more or less problems with starting the task. The resize task is the task with the smallest start areas. Therefore, the width of the steering areas are the smallest.
It was difficult for the users to position their fingers into these areas in direct setting, because their finger were bigger than the starting areas. Similar observations were men-

	t(76)=	p
direct vs 1.00	2.447374	0.0835
direct vs 0.75	2.028648	0.23
direct vs 0.50	3.480387	0.004
direct vs 0.25	3.469875	0.0045
1.00 vs 0.75	0.418726	>1
1.00 vs 0.50	-1.03301	>1
1.00 vs 0.25	-1.0225	>1
0.75 vs 0.50	-1.45174	0.7535
0.75 vs 0.25	-1.44123	0.768
0.50 vs 0.25	0.010513	>1

Table 3.11: User test 4 - results of pairwise Student's t test after Bonferroni post hoc correction to fit in the confidence interval of 95%.

direct vs	difference in means	Cohen's d
0.50	1.1428974	1.07489816
0.25	1.1394452	1.236588367

Table 3.12: User test 4 - effect size calculated due to difference in means and Cohen's d.

tioned in Forlines et al. [2007]. Not seeing where the system maps their position to a cursor seemed rather frustrating for some users. One of our users even mentioned that for his point of view his fingers were over the starting areas and the system should allow him to start, he could not do a better positioning with the knowledge he had at the moment.

Object size doesn't seem to be a problem if we use both hands.

In user test 5, which had the same size and task, direct is faster than indirect in all CDs. At this point the argument about the object size does not hold any more, but we assume that in this task the threshold is not reached and the objects are still big enough, because the task is easier for the user by doing it with both pointing fingers.
To prove this argument, we did an additional analysis which we will see later on.

Task get slightly harder with smaller CDs.

In comparison to 0.25 and 0.50 direct is still significant faster, what also seemed to be caused by the task size. Since the object control size shrinks with the CD the task may get harder. The effect is not significant enough to show any statistical effects between the different indirect CDs but still it results in the effect that direct is only better in the smaller CDs and not in the bigger.

3.8.5 User Test 5

Represents a resizing with two hands.

This user test represents a resizing done with both pointing fingers. We investigated the user performance in resizing tasks with two hands for different CDs with this test.

The measurements and the hypotheses stayed the same as in the user test before.

Experimental Design

The experimental design stays the same as in user test 4.

Method

As before is left hand controlling bottom cursor and right top.

The method stays the same as in user test 4 except that the user now uses both pointing fingers. He was told to use his right pointing finger to control the top cursor and the left for the bottom area.

Results

Direct was significant faster than all indirect settings.

The result of the REML method with user as random effect and control size as effect, which we used to analyze the results, shows a significant effect ($F(76) = 14.3284$; $p < 0.0001$).

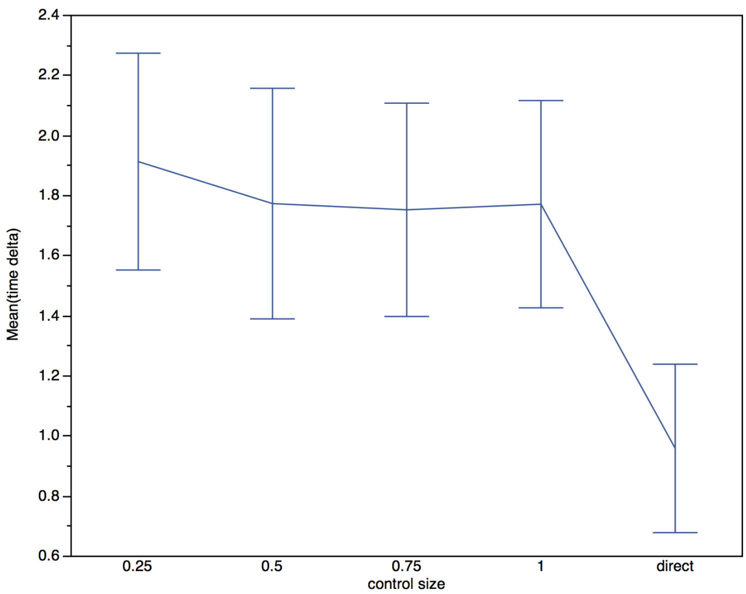

Figure 3.18: User Test 5 - mean completion time with a confidence interval of 95%.

A pairwise comparison of the CDs shows that the direct setting has a significant difference in comparison to all indirect CDs. Detailed results can be seen in Table 3.13. Due to this significant results did both hypotheses hold.

To determine the effect size we grouped all indirect settings as already done in user test 3, since there was no statistical difference between them and compared the means and calculated Cohen's d in comparison to direct. The results can be found in Table 3.14.

The mean completion time of direct was 0,9591713 seconds. It was about 44% faster than indirect.

Discussion

Not so many positioning problems compared to user test 4.

In user test 4 we observed that the user had problems in direct setting with positioning his finger into the start areas. User test 5 has the same size of steering and start areas, but the problem seems to be less severe, since both pointing fin-

	t(76)=	p
direct vs 1.00	5.681669	<0.001
direct vs 0.75	5.55091	<0.001
direct vs 0.50	5.695306	<0.001
direct vs 0.25	6.672431	<0.001
1.00 vs 0.75	0.130769	1
1.00 vs 0.50	-0.01364	1
1.00 vs 0.25	-0.99076	1
0.75 vs 0.50	-0.14441	1
0.75 vs 0.25	-1.12153	1
0.50 vs 0.25	-0.97712	1

Table 3.13: User test 5 - results of pairwise Student's t test after Bonferroni post hoc correction to fit in the confidence interval of 95%.

	difference in means	Cohen's d
direct vs indirect	0.8439852	1.341189494

Table 3.14: User test 5 - effect size calculated due to difference in means and Cohen's d.

gers were not affected by each other like the thumb and the pointing finger. To test if this can be supported by statistical values, we will test this in the additional test section.

As before, we assume that the significant faster performance in the direct setting results from the lower cognitive load caused by the more direct and native interaction (Forlines et al. [2007], Schmidt et al. [2009]).

The missing of statistical difference between the indirect settings indicates that the user has no problems in completing these kind of task at any tested CD, even if the task is this small. This may only be possible because of the very short steering areas.

3.8.6 Additional Analyses

Is the interaction with two hands better than with one hand?

In our discussion of user test 4 we stated that the object control size may be reached when the user is no longer capable of solving the task without major positioning problems in direct setting.
In user test 5 the user did not seem to have this problem, even if the object size was the same. Therefore, we stated that it seemed to be easier for the user to perform this task with two hands instead of one. To support this statement we did some additional data analysis, to test if the user performance is better with two hands than with one.

Experimental Design

We used the given data.

To test this we used the data we had received from the user test 2, 3, 4 and 5, since user test 2 and 3 and user test 4 and 5 are the exact same task just done with either one or two hands. We took the input technique as second independent variable. Since we had randomized the control sizes and the task type we assumed that we counterbalanced the learning effects.

Therefore, we did 2 additional analysis, each with the independent variables input method and control size. In the first analysis we compared user test 2 and 3, which were the rotation tasks. In the second analysis we compared user test 4 and 5, which were the resizing tasks.

For each of these analysis we tested the following hypothesis:

- **H:** There is a significant difference in completion time for the given task using one hand or two hands.

Therefore, we used the measurement completion time as before. All task sizes are described in the user test chapters above.

Method

All method related information can be taken from the chapters about the user tests, because we already these methods.

Results

Effects of control size and task type were found.

Rotation We used the REML method with user as random effect and control size, input method and control size ∗ input method as effects to analyze the data. The result indicates a significant effect of control size (F(171) = 36.3537; $p < 0.0001$), which is equivalent to the results in user test 2 and 3, where in both cases control size does have a significant effect.
The results also indicates a significant effect of input method (F(171) = 170.3921; $p < 0.0001$). This is also indicated when comparing the graphs in Figure 3.19, since the two hand mean line and its confidence intervals stay under these of one hand all the time.
There was no combined effect found for input method ∗ control size (F(171) = 1.3455; p = 0.2551).

Therefore, the hypothesis is confirmed. The two hand input is significant faster than one hand.

We analyzed the effect size of the input method by comparing the means of each user test and calculating the Cohen's d. The result can be found in Table 3.15.

	difference in means	Cohen's d
one hand vs two hand	1.8163024	1.10877192

Table 3.15: Rotation - effect size calculated due to difference in means and Cohen's d.

The mean completion time of two hand was 4.2670993 seconds. It was about 30% faster than one hand.

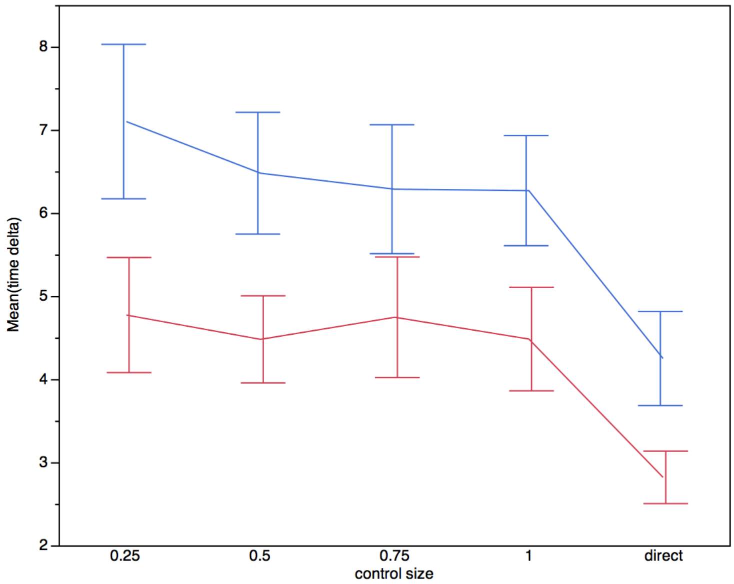

Figure 3.19: Rotation - one hand vs two hands. This dataset is the combination of user test 2 (blue) as one hand and user test 3 (red) as two hand. This figure show the mean durations with a confidence interval of 95%.

Resizing The analysis was similar to the one in rotation and resulted in the same general effects.
Like in rotation we used the REML method with user as random effect and control size, input method and control size ∗ input method as effects to analyze the data. The result again indicates a significant effect of control size (F(171) = 11.3249; $p < 0.0001$), which is equivalent to the results in the user test 4 and 5, where in both cases control size does have a significant effect.
The results also indicate a significant effect of input method (F(171) = 89.2240; $p < 0.0001$), which is again similar to rotation. Like before, this is also shown when comparing the graphs, Figure 3.20, where the two hand mean line and its confidence interval stay under one hand all the time.
Like in rotation, no combined effect found for input method ∗ control size (F(171) = 0.5261; p = 0.7167).

Effects of control size and task type were found.

The two hand input is significant faster than the one hand. This supports our hypothesis.

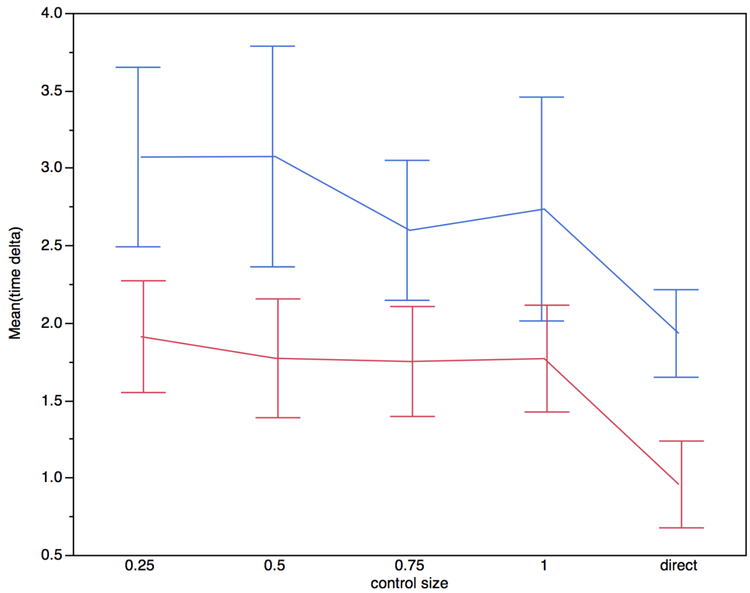

Figure 3.20: Resizing - one hand vs two hands. This dataset is the combination of user test 4 (blue) as one hand and user test 5 (red) as two hand. This figure show the mean duration with a confidence interval of 95%.

We analyzed the effect size of input method as in rotation by comparing the means of each user test and calculating the Cohen's d. All results can be found in Table 3.16.

	difference in means	Cohen's d
one hand vs two hand	1.0501648	1.011091425

Table 3.16: Resizing - effect size calculated due to difference in means and Cohen's d.

Since the mean completion time of two hand was 1.6343595 seconds it was about 39% faster than one hand interaction.

Discussion

Both analysis showed a significant effect of task type, resulting by two hand being faster than one hand. This indicates that two hand interaction is better than using one hand for our constructed task. This could be explained with the fact that if we use one hand, the thumb is biased by the pointing finger and vice versa. In our task it was not easy to see both cursors at a time. While operating with one hand, moving one finger affected the other and since they did not have to perform the exact same movement this could cause problems. The not biased separate pointing fingers seem to be a more appropriate interaction to solve this tasks.
This indication was supported by the report of four users, who told us that these tasks felt unnatural with one hand. 20% seem to be quite few, but we did not ask the users in special, if the task felt unnatural. Therefore, it is possible that much more users support this observation.

Results match the observations and may be caused by the biased fingers in one hand interaction.

Nevertheless, we can conclude that the user did perform faster, while using both hands instead of one, even if we could have assumed that controlling both hands separately would be mentally more difficult.

Two Hand is faster than one Hand in our tests.

Chapter 4

Summary and Future Work

In this chapter we now want to give a short summary about what we planned to investigate, what we did, what the results were, what we learned from them and what we can do with these in future work.

4.1 Summary and Contributions

Can we reduce the control size without user performance effects?

Our vision of a future work system is an indirect multi touch system as introduced in the beginning of the thesis. To use such a system the user has to control it with an absolute mapping. To reduce the size needed by the touch area or to make space for widgets, our idea was to use a smaller touch input as control for the output, but we feared that the user performance is maybe affected by this smaller CD, since they have some disadvantages.

Answered for tapping tasks.

In case of tapping tasks Arnaut and Greenstein [1985] already worked on our research question, even if their system was much smaller than ours, which may have an effect as shown in the work by Accot and Zhai [2001]. They showed that the absolute control size is important and hypothesize that different muscle regions have different preciseness.

Concentrate on tasks with constant contact of the finger with the touch surface.

Nevertheless, we decided to test tasks that require permanent contact with the touch surface and not on tapping. We created five user tests with three different steering tasks to test if there is any significant difference regarding time between four different indirect CDs and the direct setting. The tasks were designed to cover most of the possible interactions a user can do.

Limitation in cursor positioning.

We had an early finding that the possibility to reduce the control size depends on the count of fingers and size of the objects since the touch system does not allow to position two cursors next to each other. This effect is increased by smaller control sizes.

No effect in indirect settings found.

So we tested only those tasks, which were solvable at all tested CDs. In user test 1, 3 and 5 direct was significant faster than all indirect CDs and all indirect CDs were statistically equal. User test 2 has the same result and a small effect in comparison of CD 1.00 with 0.25. User test 4 showed only a significant effect in comparing direct with CDs of 0.25 and 0.50. All these results combined indicates that the user effect on completion time is not existent or very small when comparing different indirect CDs. The direct setting seems to be superior in all task types if the objects are not to small.

Raised difficulty cancels cursor acceleration.

We assume, that the speed improvement we found for smaller CDs is destroyed by the control of the user to stay into the areas. The permanent control, that the cursor is in the area and the adjustment of the movement to the already seen, gets more difficult with smaller CDs, because of the cursor acceleration, what cancels the speed improvement.

Direct is superior on most tasks.

The direct setting was also better than all indirect settings in most user tests, what seemed to be caused by the lower memory load of the more intuitive interaction. We had to exclude user test 1 from this results.
This seems to lose it's validity if the task get to small: user test 4 showed, that direct is not better than indirect, which we explain by the user's problem to put his finger into the starting areas because of their smaller size.

This effect did not show up in user test 5, even if the steering areas had the same size and shape. In our additional analyses we showed that the tasks seemed to be easier or the user performance improved, if he used both hands with one finger and not two fingers of one hand.

Additional analyses: one hand vs two hand

Therefore, we learned that we can reduce the size of the control without influencing the user performance if the tasks stay solvable and if he has to stay in permanent contact with the touch surface.

Direct is faster and different indirect CDs seem to have no effect.

Nevertheless, the indirect interaction is a good technique for future systems because of the ergonomic advantages we described in the introduction, Voelker et al. [2013]. Working on indirect systems for longer periods of time is more comfortable than direct working. Additionally, it is possible that people compensate the time difference by training. Working with the indirect system for a longer timespan may result in faster interaction.

Even with these results indirect has some benefits in comparison to direct.

4.2 Future work

There were several analysis we could not investigate any further due to the lack of time in this thesis. They would be interesting to be taken up again in future work.
For example we did not find evidence that anyone tested if the Steering Law (Accot and Zhai [1997]) does hold for indirect touch. We could use our user test 1 and the circle task presented in Accot and Zhai [2001] which we already implemented, to answer this question.

Many data analysis were not handled because of time.

Additionally, we could investigate the performance effects for more complex tasks. We had a combination of resizing and dragging for our user test, but dropped it due to the duration of the user study and our test user complaining about too much friction.

Test more complex tasks.

An factor that we measured but not analyzed was the count of retries. An indication how often a task had to be performed before completing is a statement that could be interesting to know in systems were failures are critical.

How can the users' mistakes be taken into consideration?

How about systems that require preciseness not speed?

Furthermore, the preciseness could be an interesting topic. In tasks where the user had to be very precise in movement and not fast, the smaller CDs would likely be worse than bigger ones. CDs above 1.00 could even receive better results, which needs to be tested in the future.

Leaving the analysis we could have made with our data to answer different research questions, we got some new results, which should be investigated.

How small can the CD get?

At first we did not find any effects in performance caused by the change of control size in indirect settings if the tasks stay solvable, but, as Accot and Zhai [2001] stated, it is a trivial question if we just shrink the control size far enough. It would therefore be interesting to investigate even smaller CDs.

How does objective size and control size interact?

Second, an open question is the effect of object size in interaction with control size. When do objects get too small to be used in indirect systems and are these sizes different for different control sizes?

Do learning effects erase time difference?

It would also be interesting to know if the indirect performance gets better with more training and therefore the direct loses its speed advantage.

Use our results to build systems with better user performance.

Finally, we want to construct a system that will benefit from our results by reducing the control to have space for special controls or other helping tools and which is better than a system with the CD of 1.00 or a direct system.

Appendix A

Consent Form

Consent form that every user had to sign. One was given to us and a copy to the user, if he wanted to.

Informed Consent Form

Touch state switching thresholds

PRINCIPAL INVESTIGATOR Rene Linden
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Phone: 0157-77818974
Email: Rene.Linden1@rwth-aachen.de

Purpose of the study: The goal of this study is to measure user performance changes while completing steering tasks on an indirect touch system with different control sizes. Participants will be asked to place their fingers into the starting areas and move the cursor through the steering area. Touch signals and finger positions will be used in the analysis.

Procedure: You will be asked to use your fingers to move the cursors through the steering areas. This study should take about 60 minutes to complete. After the study, we will ask you qualitative feedback about the procedure.

Risks/Discomfort: You may become fatigued during the course of your participation in the study. You will be given several opportunities to rest, and additional breaks are also possible. There are no other risks associated with participation in the study. Should completion of either the task or the questionnaire become distressing to you, it will be terminated immediately.

Benefits: The results of this study will be useful for determining the effect on user performance in indirect touch systems due changes in the control size.

Alternatives to Participation: Participation in this study is voluntary. You are free to withdraw or discontinue the participation.

Cost and Compensation: Participation in this study will involve no cost to you.

Confidentiality: All information collected during the study period will be kept strictly confidential. You will be identified through identification numbers. No publications or reports from this project will include identifying information on any participant. If you agree to join this study, please sign your name below.

_____ I have read and understood the information on this form.
_____ I have had the information on this form explained to me.

Participant's Name	Participant's Signature	Date
	Principal Investigator	Date

If you have any questions regarding this study, please contact Rene Linden at 0157-77818974 email: Rene.Linden1@rwth-aachen.de

Figure A.1: This is the consent form the user had to sign.

Appendix B

Questionaire

Short questionaire that had to be filled by the user, except the user ID, which was determined by us.

User ID: _____

Gender: ___________________

Age: _____

Occupation: ____

-- After participation --

Comments:

Figure B.1: Short questionaire that had to be filled by the user.

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