Influencing Tabletop Interaction Speed: Directness and Device

by

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Abstract

This thesis presents two studies into factors that influence speed of passing documents on a tabletop display. Document passing consist of rotation and translation tasks. Two interaction techniques that support both rotation and translation, *RNT* and *Corner,* were compared in both studies. The *RNT* technique is an semi-integral technique and combines rotation and translation. The *Corner* technique is a separate technique and requires a separate rotation and a separate translation movement.

This thesis tried to find the reason behind the performance differences of prior studies and to find which underlying factors influence performance on document passing tasks using a tabletop display. The first study investigated the influence of movement distance, precision and handle size, using 8 participants. The second study investigated the influence of directness and device, using 18 participants.

The results of the studies could not find the reason of the contradicting results from the prior studies. The semi-integral technique, *RNT*, was the fastest technique in every condition, estimating a 47% improvement in the first study and 11% improvement in the second study. Furthermore, it presented that direct interaction was 36% faster than indirect interaction and had a 40% lower workload. The 3 devices compared in the second study, a stylus, a glove finger and a mouse, did not show a significant performance difference.

Keywords: tabletop displays, rotate-translate, human computer interaction, interaction technique

Abstract - Dutch version

Dit verslag presenteert twee studies naar factoren die de snelheid beïnvloeden van het verplaatsen van documenten op een digitale tafel. Dit verplaatsen van documenten omvat rotatie en translatie taken. Twee interactietechnieken die rotatie en translatie ondersteunen, *Corner* en *RNT*, zijn vergeleken in deze twee genoemde studies. De *RNT* techniek is een semi-integrale techniek die rotatie en translatie combineert. De *Corner* techniek is een gescheiden techniek en vereist een losse rotatie en een losse translatie handeling met het document.

Dit verslag en onderzoek probeerde de reden te vinden achter het prestatieverschil tussen de vorige studies en probeerde tegelijk te vinden welke onderliggende factoren invloed uitoefenen op het doorgeven van documenten op een digitale tafel. De eerste studie onderzocht de invloed van afstand, precisie en de grootte van de handles, in een gebruikersstudie met 8 deelnemers. De tweede studie onderzocht de invloed van directheid en het gebruikte apparaat, in een studie met 18 deelnemers.

De resultaten van beide studies kon er niet toe leiden dat de reden van de conflicterende resultaten van de vorige onderzoeken werd ontdekt. De semi-integrale techniek, *RNT*, was de snelste techniek in alle geteste condities. Deze techniek leverde een geschatte prestatieverbetering op van 47% in de eerste studie en een prestatieverbetering van 11% in de tweede studie. Verdere resultaten zijn dat de directe interactiemethode 36% sneller was dan de indirecte interactiemethode en ook een verlaging van 40% opleverde in de gebruikersbelasting. De 3 vergeleken apparaten in de tweede studie, een pen, een vinger van een golfhandschoen en een muis, lieten geen significante prestatieverschillen zien.

Acknowledgements

“O Canada”

The National Anthem of Canada

When people in the Netherlands think about Canada, they mostly think about three things: holiday, immigration and plenty of space. Almost nobody considers scientific research, how strange. Well, I did and I actually went there. What an impressive and beautiful country! It was a great time being there.

My first requisite of doing research abroad is to find a place where my research interests meet the interests of a research group. But finding such a group doesn't necessarily mean going there and joining their research. It could not have taken place without a person who was willing to adopt a foreigner like me into their group, given what it takes to overcome the language barriers, sharing the knowledge needed to participate, having the energy and patience to guide me and the funding to support me. Therefore I would like to thank Ted Kirkpatrick very much for all his efforts and energy, for allowing me to join his research projects and guiding me towards the goals of my thesis. Working at SFU until 10pm to solve an important bug in the experimental software, dropping me off in the Fraser Valley or reviewing my thesis and thesis proposal over and over, nothing was too much for him. The precise and positive comments on my writings really helped and guided me in improving these documents. Ted, thank you!

During the research projects, Stella Atkins also participated and funded my work, thank you too for making it possible. Working at SFU also meant having fellow research students in the lab. I would like to thank the GrUVi Lab members for their chats, jokes, having lunch together, helping to improve my German and the joy of beating a Brazilian lab member at table tennis and who also gave me in-depth insights into toasting bread, which even French people could not dream about.

As research was an important part of my life in Canada, spending time at a nice place to stay was as important as doing the research itself. Staying with Uncle Andy and Aunt Rika was like being adopted into their lives. They gave me a great place to stay, both physically as well as mentally. They shared their life with me in many ways, at Christmas, birthday celebrations and their daily activities and responsibilities of taking care of their Foster Parent children. I've learned and experienced a lot. Thank you for all your love! While being in Canada, I also had the opportunity to get to know my Canadian cousins better, which I really appreciated. I enjoyed babysitting their kids, getting high quality hair cuts, borrowing a mountain bike, making day trips around Vancouver and SFU. Thank you!

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Getting back and forth from Langley to SFU was not possible without Wendell. He drove me every weekday as an experienced driver to SFU - picking me up at 232 street, driving to the Portman bridge, speeding in the HOV lane and getting off the HOV just before the off-ramp to SFU, while listening to News1130. For months, I attempted to grow an apple tree by littering my apple cores near the on-ramp of Highway 1 when we drove back home. And hopefully, when I return some day, I will see a beautiful big fruitful apple tree. I would like to thank Wendell for carpooling, his positive attitude and patience, the talks we had about Physics, especially on the topic of superfluids at high temperatures. I almost helped him to get a break through, but unfortunately, I needed some more time.

I am very thankful for the love and encouragement I have received from Amanda, who became my girlfriend since I've returned to the Netherlands. And during many years of my life, I've received love and affection from my dear parents, for whom I am very thankful.

I've also received feedback and comments on my thesis from my graduation committee, while writing at the University of Twente. Thanks for your time.

Jacob Koster

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1. Introduction

A digital tabletop display is an interactive computer display mounted into or projected on a real-world horizontal table surface. The usage of tabletop displays can benefit different applications. Especially activities in collaborative work as tasks in office environments, such as planning schedules, drawing schematics or manipulating maps might benefit from the use of tabletop displays.

The tabletop display is suitable for collaborative work due to its horizontal position, size and the possibility to interact with the display together. A normal desktop computer is made for one person at a time. A tabletop display allows people to have their private workspace and a shared workspace together at one table. People can sit around the table and read, share and exchange digital objects such as documents, applicable for example in meetings or office-desks. With normal, non-digital tabletop desks, people sometimes pass papers towards each other in collaborative environments. Also an individual person moves and rearranges papers around the table to keep them readable. A tabletop display can be used to display papers and documents at the same way. If digital documents with text are used on digital tabletop displays, it preferably should support digital document passing and rotation to make correction of document's position possible. When using digital papers on a tabletop, the orientation and angle of textual elements influences the human reading performance (Wigdor & Balakrishnan, 2005). A decrease in readability of a document can be eliminated by adjusting the position and rotation of the document.

Several interaction techniques have been developed to move digital documents over a display. These techniques enable rotation and translation of digital documents. The human performance of these techniques has been compared in different user studies (Kruger, Carpendale, Scott & Tang, 2005; Mitchell, 2003; Kirkpatrick, Atkins & Koster, 2006). They show that the human performance of moving digital document tasks using interaction techniques vary. In addition, their manipulated task and interaction technique conditions vary as well. They do not sufficiently compare the various conditions or the effects of these conditions. The conditions are likely to influence performance and the influence size of each separate condition was not compared before.

This thesis addresses the likely important conditions that might affect human performance on interaction with digital documents: movement distance, handle size, precision and level of directness of 2D interaction techniques, on tabletop displays. When the influence of these conditions is known, designers of tabletop displays can improve interaction techniques to help a user perform its interaction tasks with a better performance. Also interaction techniques on tabletop displays might be improved to achieve better workload and faster task completion times.

1.1. Interaction Techniques

There are several rotate-translate interaction techniques available to interact with digital documents on tabletop displays. These techniques can be categorized as single point and multiple point interaction techniques. Examples of single point interaction techniques are: *Corner* (Mitchell, 2003), *RNT* (Kruger et al., 2005), *Wheel* (Mitchell, 2003) and *TractorBeam* (Parker, Mandryk & Inkpen, 2005). Another technique that involves more contact points, for example two fingers, is *Two Point* (Hancock et al., 2006). This section continues with details of some interaction techniques and ends with an explanation of my selection of the two techniques that have been studied.

Corner is an interaction technique often used in desktop computer interaction. Dragging inside the superimposed regions at the corners of the document rotates and dragging anywhere else inside the documents translates it. Examples of the *Corner* technique can be found in drawing programs or in manipulation with drawing objects in text processing programs. A requisite for *Corner* is the use of handles: rotation and translation is only possible using different handles and can not be executed at the same time.

Another technique is called *RNT* and stands for Rotate'N Translate, which provides integrated control of rotation and translation using only a single touch-point for input (Kruger et al., 2005). Here, integration means that rotation and translation can be done in one movement, using one contact point, for example a mouse pointer or a finger. In the center of the object is a circular region, to allow pure translation. Figure 1 illustrates these two interaction techniques including the areas and functions.

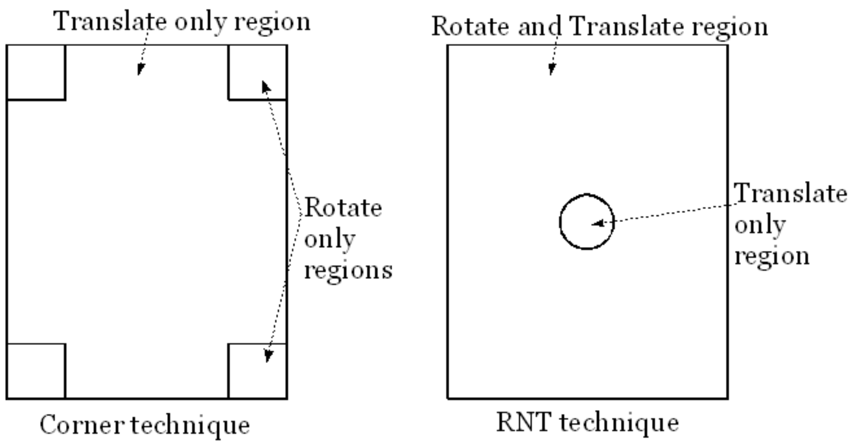

Figure 1: Corner (left) and RNT

Another interaction technique is called *Drag* and behaves similar to *RNT*; it combines rotation and translation in one movement (Mitchell, 2003). *Drag* is developed with the aim to simulate the behavior of a real-world paper moving over a desk; it adds a friction based calculation. If the document is grasped at the edge and moved around, it will rotate fast whereas touching it closer to the center will result in a slower rotation. In the latter situation, the paper would hardly rotate and mostly just translates, following the finger.

A technique using the scroll wheel of the mouse for rotation, *Wheel*, is compared in the same user study (Mitchell, 2003). Using *Wheel*, the digital document is translatable through clicking on its surface and moving the mouse. The scroll wheel is used for rotation; one rotational click on the scroll wheel results in a 5° rotation of the digital object, about the mouse pointer. Mitchell's study shows *Wheel* taking four times longer to rotate a document than *Corner*.

Modern tabletop displays (for example DViT SMART Board (SmartTech, 2006)) support multiple contact points, using cameras instead of capacitive sensing technology used in older tabletop displays, such as DiamondTouch (Dietz & Leigh, 2001). This technology enables a use of broader interaction techniques. For example, it is possible to have two points of contact from one or multiple users or have two points of contact from one hand and achieve a higher level of integrality. More than one contact point allows rotating and translating without switching modes: rotation and translation are executable together, in an integral way. The concept of integrality is explained in section 1.4. A user can rotate an object just by rotating his hand at the table, or translate by translating his hand and the object will make the same translation. This interaction technique is called *Two Point*. It is possible to use even more than two points of interaction from the same hand, enhancing the kind of interaction. A third or more points of interaction do not add an additional degree of freedom for the *Two Point* technique, but might give more freedom to use different fingers at the same time or might add more stability in case of input errors.

1.2. Directness

Operating a tabletop display can be done with, for example, a mouse. A mouse operates a cursor over a distance. Tabletop displays support interaction directly at the display: by touching the display at the same position of where the interaction should be. It feels like the cursor is at your fingertips: direct interaction. An opposite interaction level is called indirect interaction, for example the normal mouse use. This section looks closer at the definition of the two most opposing levels of directness; the next section shows factors influencing the level of directness.

Using direct interaction, the user's hand and the object are collocated. Examples of direct interaction in the real-world can be found in using markers on a white board, or moving a paper over an office desk. In direct tabletop interaction the movement of the user's hand, control, is identical to the object movement, display. In other words: direct interaction does not allow mappings between workspaces: the hand's and object's workspace are at the same location, working in the same space.

Indirect interaction means that the user's hand moves in a different way or in a different space than the document does. In other words, it can be defined as mapping different workspaces to each other: hand and object workspaces. An example of indirect interaction is the use of a normal mouse. Another example is a situation where a big screen is used to project an image. And at the same time, the user's hand can work at the big screen by moving its hand on a 15 by 15 cm space, say a touch pad. In this situation a mapping between the hand's space and big screen is taking place. Also mappings in the reversed order can be possible, where a large movement can result in a small movement in the digital environment.

1.3. Conditions Influencing Directness

There are different levels of directness between direct and indirect interaction. Some interaction conditions influence directness, so untangling these conditions helps to investigate directness itself. This section focuses on three conditions that influence directness on tabletop interaction: 'size of actual movement', 'visual offset' and 'hand posture and device'. Not all of these conditions are features of directness itself; they are confounded within directness. For example, a comparison of a direct technique versus an indirect technique not only varies directness, but also varies hand posture and device.

Other conditions between direct and indirect interaction may still exist, but this thesis concentrates on differences of directness between two studies conducted in the past, Kruger's and Mitchell's.

Size of actual movement

A mouse is mostly used as an indirect device: both its directness and the size of actual movement are different. The mouse does not have to move as far as oppose to direct, because in direct interaction, difference in distance between the user's hand and the moving document do not exist. Both the hand and the document travel the same physical distance. In the indirect case, this does not have to be true: an indirect mouse can move 10 cm while the document at the display moves twice as far.

Visual offset

Another factor influencing directness is the degree of visual offset. The offset is the distance between the hand's location and the digital document. In direct interaction, the hand and document are collocated so the distance offset is zero. In the indirect situation, the mouse lies besides the monitor or keyboard, which causes a visual offset. If a user is doing manipulations without a visual offset it would see both the workspace and its own hand together, in the same field of view.

Hand posture and device

Using a stylus to operate a tabletop display versus a mouse not only causes differences in size of movement, but also causes a difference in hand posture. This might influence performance as well. This distinction was determined during the course of research to require modification. Besides hand posture also the feedback of command selection changes. Every kind of device has different ways of giving feedback. A mouse button gives a sensible (push until stopped) and audible (click sound) response when hitting it. A stylus or user's own finger, for example, does not make use of a button to control the cursor but replies or confirms the control using physical contact of the table in combination with a quiet sound when touched, as a command selection. In other words, when a user is operating a tabletop display, touching the display confirms that the user is in control of the document. The sensible and audible confirmation might have an effect on performance.

1.4. Integrality and Separability

When moving physical papers on a desk, rotation and translation are both unavoidably executed together. In digital environments, it is possible to separate these tasks and execute them independently. For example, it is possible to disable translation when rotation-only is selected. These options give opportunities to search for combinations of techniques that result in a better performance.

An interaction technique that supports combined rotation and translation can be seen as an integral technique, because rotation and translation are performed in an integral way. Others keep these operations distinct; they can be seen as separate techniques. Jacob et al. (1994) defined integrality in a perceptual way, they say that “attributes that combine perceptually are said to be integral; those that remain distinct are separable.” In document passing, translation and rotation are perceived integral; every translation has a rotation, although it maybe a null rotation.

The interaction techniques, as described before, fit into this integrality taxonomy. *Corner* is the least integral interaction technique because translation and rotation are totally separated from each other. A user needs a second mouse click and move to switch between these modes. The *Wheel* technique separates these modes as well, but allows a user to manipulate both modes in parallel. *Drag* and *RNT* both do translation and rotation in a fluid and semi-integral motion. One can also use these techniques in a more separable and less fluid way, by using the non-rotation spots. The 3rd degree of freedom (rotation) in *RNT* and *Drag* is achieved in combination of the first two degrees; it is a 2+1 DOF technique. A translation is needed when one likes to rotate.

The *Two Point* interaction technique is the most integral technique of this section, because rotation and translation are perceived in the same way as they are executed. Rotation and translation are influenced by both the motions and positions of the fingers. *Two Point* interaction has a true three degrees of freedom, every degree of freedom is controllable independently.

1.5. Crossover Effect

The human performance of tabletop display interaction techniques is influenced by several conditions. To find out how well interaction techniques performed, different people have performed user studies. The interaction techniques *Corner* and *RNT* were compared in several studies using controlled settings (Kruger et al., 2005; Kirkpatrick et al., 2006). Also, *Corner* and *Drag* were compared (Mitchel, 2003). These techniques can function without the use of special devices; they only define the behavior of a dragged object on certain touch positions. See sections 2.6 and 2.7 for more details on these studies.

Note that with respect to Kruger's study, only the document passing task is meant (task 2 of his study) (2005). Other tasks he performed are not similar enough to compare to Mitchell's (2003) or Kirkpatrick's (2006) studies: Kruger's task 1 used a single distance and a very high precision; task 3 was a collaborative task where participants influence each other (2005). Section 2.7 presents the details.

Previous studies show contradicting results of human performance: in Kruger's study *RNT* was the fastest technique (2005) while in Mitchell's study *Corner* was the fastest (2003). These contradicting results are called the crossover effect. The task and interaction technique conditions differ between both studies. An example of a task condition is movement distance; it denotes how far the digital document should be moved. An example of an interaction technique condition is handle size, and stands for the size of the corners in case of the *Corner* interaction technique. In this thesis both the technique and task conditions are termed factors.

Another difference between these two studies is directness. Kruger used direct interaction in his study: the user holds a stylus and touches the object with the tip at the display, while Mitchell uses indirect interaction: the mouse moves at a separate workspace. This difference in directness might also influence performance of interaction techniques. Performing a study on directness itself is possible if the effects and consequences of the other conditions used in previous studies are clear. Otherwise, choosing a certain distance might have more impact than directness and can confound the results. So, no certain conclusions can be made if other factors are not kept constant.

The factors used in both Mitchell's and Kruger's studies might achieved better results for the interaction technique tested in each study. Figure 2 illustrates the task time results of both studies, including the performance crossover effect. It is unknown why *Corner* resulted as the fastest technique for Mitchell's and Kirkpatrick's studies while *RNT* is the fastest technique in Kruger's study. The left side of the figure presents results of two studies with similar results, Mitchell's and Kirkpatrick's: *Corner* is the fastest interaction technique. The same interaction tasks performed with *Corner* took less time than if they were performed with *RNT*. To the right, Kruger's study shows that *RNT* took less time and *Corner* took more. This thesis describes two studies that investigated the influence of factors that were varied between these studies.

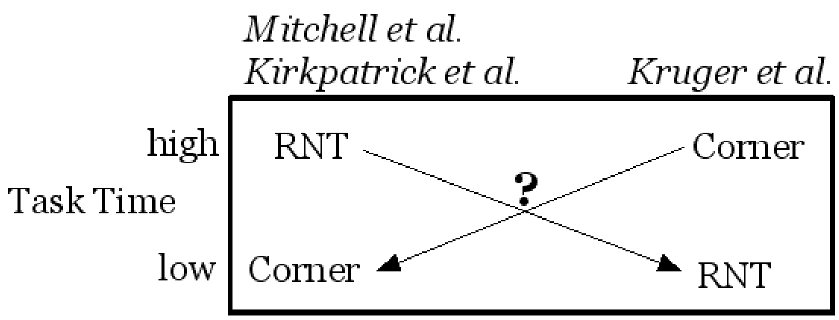

Figure 2: crossover effect illustrated; low task times are better

1.6. Research Questions

The crossover effect can be caused by many factors. The most likely factors involved in the crossover effect are the conditions of the studies: the task and interaction technique conditions. Some of these important conditions are: distance, handle size and precision. Also, the levels of directness might play an important role in the crossover: size of actual movement, device and visual offset. More conditions are of interest in tabletop interaction: target orientation and direction of movement. The latter factors might influence performance, but are not likely to influence a separate technique (*Corner*) more than an integral technique (*RNT*).

There are several reasons to compare only *Corner* and *RNT*. Both techniques have been compared before and comparable data from controlled user studies is available. *Corner* has the property to separate rotation from translation. Including *Corner* means including an instance of the class of separable interaction techniques. The other technique, *RNT*, is an integral technique and is an example of the integral class. Another reason is that *Corner* is a well known and often used technique. Adding more techniques in a user study requires more time and effort of the participants. Therefore only a small selection of interaction techniques can be tested.

The usability of tabletop display document passing applications and tasks can be evaluated and measured in several distinct ways, such as: speed, user preference, effort and the possibility of collaborative work. Both collaborative tasks and individual tasks contain primary operations such as rotation and translation. These primary operations can be evaluated on tabletop displays, using these measures: speed, effort and user preference. The speed of tabletop tasks are expressed as task completion time: the time between the start of a task and the successful completion. Also 'human performance' is used as a synonym for speed. Subjective measures as effort and preference are also included in the study and presented in the workload sections 4.4 and 6.4.

The question this thesis tried to answer is as follows:

> *Q1. What is the reason of the crossover effect in human performance as seen in Mitchell's and Kruger's tabletop display studies on document passing?*

The crossover effect between the Mitchell's and Kruger's studies has to be caused by different factors or conditions the studies were executed in. Mitchell and Kruger both described their study in detail. Differences in both studies, which are influencing performance, are too many to investigate at once. Limited time is available during a user study. So, only a few factors could be selected and be part of the first study. The first study investigated the effect of three factors, movement distance, handle size and precision, using direct interaction with the user's finger at the tabletop display.

These three factors were chosen because it is likely that they influence an integral technique more than a separate technique. Section 3.4 describes the expected influence of these factors in detail; this section summarizes and foreshadows the arguments.

Movement distance is likely to favor an integrated technique because rotation and translation are executed together. A longer distance means a longer translation and for integrated techniques it gives more time to rotate. With separated techniques, rotation and translation are not influenced by each other. The handle size of *RNT* and *Corner* differ in a functional way: handles for *Corner* are obligatorily whereas for *RNT* they are not necessary. The speed of pointing at a handle is influenced by the size of the handle, as predicted by Fitts' law (MacKenzie, Sellen & Buxton, 1992). The frequency of handle use likely differs between the techniques and therefore *Corner* is helped more than *RNT* if the handles are larger. Loose precision is likely to favor integrated techniques more than separated techniques because a coarse movement using an integrated technique can be sufficient to bring the document at the desired position. If one uses a separate technique, always a time consuming handle change is needed for combined rotation and translations.

Q2. What is the influence size of three factors: distance, precision and handle size on document passing?

The first study is called 'Factors influencing tabletop speed' and investigated three factors: movement distance, precision and handle size. A second study 'Device and Directness' was required to find the influence of device and directness. The hypotheses of the first study are given in section 3.4. For the hypotheses of the second study, see section 5.2.

This thesis is structured as follows. Chapter 2 presents context information about tabletop work and dives more into detail at various subjects related to the research questions. Chapter 3 and 4 explain why and how the factors were investigated in user study 'Factors influencing tabletop speed'. Chapter 5 and 6 present the influence of directness and device on tabletop interaction. Chapter 7 and 8 present conclusions and the circumstances the whole study was executed in.

2. Tabletop Interaction Technology – State of the Art

This chapter describes the tabletop display technology followed by a general history of interaction techniques. Next, some interaction techniques on tabletop displays and collaborative work on tabletop displays are described. The chapter ends with describing document passing interaction techniques developed for tabletop displays.

2.1. Tabletop Technology

A tabletop display is an interactive display that is positioned at or in a desk or a table. Tabletop displays started to be used and developed from 2001. This section describes a few tabletop display technologies.

A tabletop display sensing technique was presented in 2001: the DiamondTouch (Dietz & Leigh, 2001). Several different people can touch the display simultaneously, without interfering each other. The display is able to distinguish different users by using modulated electronic fields which are capacitive coupled through the users. Every touch point at the display has the charge from a specific user and enables the display to separate actions between users.

A tabletop display using a rear projection system is named SMART Board and uses digital cameras in a bezel. These cameras are used to sense the touch position at the display. One can use select a pen out of a few different colors and write at the display. It detects which pen is missing from the tray to assign the appropriate writing color (SmartTech, 2006).

A fairly new tabletop display technique is developed to enable high resolution multi-touch sensing on rear-projected interactive surfaces (Han, 2005). This technique uses reflection of light at the location of touch and does sensing with a digital video camera from behind the display. Until now, no tabletop displays can be bought using this technique because it is in development stage.

The two studies as described and performed in this thesis were using a different tabletop display system. A combination of a motion track system and a ceiling mounted projector enabled tabletop display interaction. Detailed information is presented in section 3.8.

2.2. General History Interaction Techniques

This section describes a general history overview on interaction techniques and ends with techniques developed specifically for document passing.

In 1954, Fitts formulated a model to predict the time required to rapidly point at a certain area. He performed several experiments, including one using reciprocal tapping tasks. The distance between start and end point and the width of the end point were varied. The results found a relation between distance, tolerance (e.g. target width) and speed. His results were often used and cited in HCI. Several refinements and extensions were made and published, see section 2.5 for more details.

Jacob writes about the input / output bandwidth difference from a computer to a human (1996). Humans receive far more data from the computer than they could input in the computer. He cites that direct manipulation interfaces were making progress already back in 1983. Also the gap between the user's intentions and the actions necessary to input them into the computer should be reduced. He states that we should make the gap between the user's input actions as close as possible to the user's thoughts that motivated those actions (1996).

A survey by Ziegler presents a graph with a range of generations of user interfaces by communication bandwidth (1996). Starting with Teletype systems and full screen menus ending with multi modal input and augmented reality with voice and gestures input.

In the near past, people still work on graphical user interfaces and search a way to interact with computers and their extend, such as PDAs. Experiments with wall-size displays, for example electronic white boards, already present features that are also available in some tabletop displays applications (Guimbretière, Stone & Winograd, 2001). In the same year, the DiamondTouch was presented as a tabletop display (Dietz & Leigh, 2001). Several different people could touch the display simultaneously, without interfering each others work. The display is able to distinguish different users by using modulated electronic fields which are capacitively coupled through the users. Every touch point at the display corresponds to a specific user.

A year later a study was performed using a 20 inch LCD display laid down at a table, called the e-Table (Kruger & Carpendale, 2002). Using two mice as input devices (instead of touch sensitive input) participants performed a puzzle game. Observations were done to see how people interact and aimed to design better and bigger digital tables in the future.

Later, some people were comparing different interaction techniques on document passing using the tabletop display for collaborative applications; presented in the consecutive sections. Users could use a tabletop display while sitting around the table and handing over documents or other digital artifacts, while keeping in mind the analogy between a real world desktop table and a future desktop table with an integrated display.

2.3. Tabletop Interaction Techniques

A tabletop display not only enables document passing but also a broader use of interaction techniques. This section describes several techniques that deal with problems such as far distances, group coordination and conflict and ends with an observational tabletop study.

A novel interaction technique, *TractorBeam*, was developed to reach objects on the far side of the table (Parker et al., 2005). They used a Polhemus Fastrak to sense 3D coordinates for pointing (Polhemus, 2007). Tabletop displays can not receive 3D coordinates. Using a stylus for remote pointing, they show that large objects (12 cm width) benefit significantly from pointing instead of using direct touch on a distance of 78 cm. The stylus could be used for both touching and pointing so participants could choose the method of moving the objects.

Using a different device called TNT-block, results show a better performance than *RNT* (Liu, Pinelle, Sallam, Subramanian & Gutwin, 2006). TNT-block uses a sensor in a cylindrical plastic block so users can rotate the block and the digital artifact follows the rotation. They developed the *TNT-block* technique to better support large rotation angles.

A few interaction techniques were compared focusing on group coordination and technique differences (Nacenta, Pinelle, Stuckel & Gutwin, 2007). They used interaction techniques representatives of different classes according to their coordination point of view. These four classes are worth mentioning, all techniques used a stylus as input device. Firstly, *Drag-and-drop* activates dragging the object with touching it and lifting from the object means letting it go; a direct technique. Secondly, *Radar View* shows a miniature image of the entire table's contents and users are interaction with the table through their miniature space in the same manner as with *Drag-and-drop*; an indirect technique using a gain. Thirdly, *Pantograph* uses a colored line connected from the physical position of the user, through the tip of the pen unto the table; indirect technique. They amplified the length of the line: the farther away the stylus from the start of the line, the farther away the line reaches over the table. *Telepointer* is similar to Pantograph, but does not have the line connecting the cursor to the pen tip. Fourthly, *Laser Beam*, the user points the stylus to the table and the cursor appears at the intersection of the pen's direction and the tabletop plane; an indirect technique. They measured conflict of using an object at the same time. Participants were working in a group op three persons. The *Radar View* technique was the most conflict generating technique during the user study. Participants could not see each other working because of their own miniature space. The *Laser* technique was the least conflicting, probably because everybody could see where someone else is working. As a result, they point out that in collaborative work, using a shared working space the between the cursor and the individual has a significant role. Also, it depends strongly at the task which interaction technique is the most suitable.

A somewhat different study shows results of observations where users chose to interact with a tabletop at their own volition (Ryall, Forlines, Shen, Morris & Everitt, 2006). People could just walk up and start using the tabletop or choose to read simple instructions if they liked to. They observed four applications over a period of two years in different settings. One tabletop display was running at the lobby area in a research lab running different games; another application was running a biologists' field data annotation program; another tabletop application was running at a three-day conference with an educational game, a finger-paint program. They analyze the usage data recorded during these events and present some common usage patterns. Results show that often ambiguous touches occurred by for example touches with the wrists or elbows. Also people tend to use the display with single-finger interaction. The users need to get familiar with the multi-finger and multi-hand use of the table. Also they point out that GUI elements are often aimed at mouse use and therefore need modification for tabletop finger usage. Finger usage at a tabletop display is often coarser than mouse usage.

2.4. Collaborative Work on Tabletop Displays

Interaction techniques like *Corner* and *RNT* are made to move or rotate digital objects, such as documents or rectangles. In drawing programs, rotations of objects occur often. In other computer applications moving text boxes or drawing lines is a common task for many computers users. But it is difficult to manipulate the same document at the same time with more than one person. Typically, only one keyboard and mouse are connected to a computer and sharing them is inconvenient. Tabletop displays lie horizontally and can give access for both viewing and manipulation by more than one person at a time. Modern tabletop displays can distinguish and handle multiple points of input simultaneously for multiple users. This enables working at the same display in a collaborative way. Various tabletop studies have been performed on collaborative work. The following paragraphs present a few.

For evaluating collaborative tabletop displays, various test cases have been developed, for example a room furniture layout application, the RoomPlanner (Wu & Balakrishnan, 2003). They created the room planner application to explore the use of multi-finger and whole hand gestures. Gestures such as tapping with the fingers and making a horizontal shape with the whole hand were used to control the tabletop display. Also two fingers from the same hand could rotate objects; the rotational center was marked with one finger and the angle with the other.

Cooperative gestures could increase participation or awareness of important events on groupware systems (Morris, Huang, Paepcke & Winograd, 2006). Deletion of large amounts of content or leaving a running tabletop application can only be done as a group. They also demonstrate a throw-and-receive gesture for picture passing from one person to another over long distances. Another technique uses aiming to receive and manipulate a picture that is out of reach. Also user proximity is taken into account as a design consideration for cooperative work on tabletop displays.

The effect of group size in cooperative work and the effect of the size of the tabletop display were investigated in a user study with participants who were assembling a poem (Ryall, Forlines, Shen & Morris, 2004). For a group, up to four persons, they found that the size of the tabletop display (80 cm or 107 cm) did not show a significant difference but group size did increase the overall speed of collecting a poem significantly.

The research conducted in this thesis is primary about single user operations such as rotation and translation rather than group operations or collaboration between users. The information gathered about interaction technique factors can be used to improve advanced or more comprehensive interactions. For example, the effect size of distance or handle size investigated in this thesis and distance and handle sizes are generally used in different tabletop applications. Also the effects of direct interaction versus indirect interaction using different devices on tabletop displays can be beneficial, for example, remote gesturing or techniques working over a distance.

2.5. Tabletop Interaction and Fitts' law

It takes time to move an object with your hand over a distance. For example, one can grab a mug over a distance of 20 cm or over a distance of 40 cm. The distance is doubled but it does not take exactly twice as long. Clearly, distance is not the only factor influencing movement time. It takes several intermediate jobs to grab a mug, such as moving your hand, grabbing the mug when the hand is close enough, moving the mug over the appropriate distance and finally slowing down and letting the mug stand still. This example illustrates some of the factors influencing moving an object in real life. For tabletop interaction similar and comparable issues happen. When moving a digital object, the mouse pointer needs to go to the object, click inside the object, move the object and finally release the object at the end position.

Several studies investigated into the movement time in human psychomotor behavior. In HCI, the Shannon's formulation of Fitts' law is popular and often used (MacKenzie et al., 1992). Fitts' law shows the relation of speed/accuracy on aimed movements. The accuracy in moving objects on a tabletop is influenced by the target's width: the smaller the target, the higher the accuracy. Also, the smaller the target, the lower the speed. In Shannon's formulation, the movement time (*MT*) is determined by the log of the ratio of distance to width:

$$MT = a + b \log_2 (\frac{A}{W} + 1)$$

Where *A* (movement distance) and *W* (width of target) are both measures of distance. The intercept (*a*) and slope (*b*) coefficients are empirically determined constants (MacKenzie et al., 1992). The ratio within the logarithm would be without units, as dimensional analysis suggests the distance units for *A* and *W* cancel.

To make matters concrete, given an example calculation with two distances (40 and 80 cm) and two target widths (4 and 8 cm), the movement time with a distance of 40 cm and a target width of 4 cm would equally perform as 80 cm distance and 8 cm target width. These width and distance values do not purposely correspond with a study but illustrate the effect of the width of target on movement time. The constants *a* and *b* are not determined in this example and are kept constant.

2.6. Tabletop Performance Studies: Corner, Wheel and Drag

Current tabletop displays support high resolutions and allow reading of displayed digital documents. Several studies investigated how to enable document rotation and translation considering human performance and workload. This section describes a study that compared three interaction techniques on document rotation and translation.

The orientation problem of readable objects on tabletop displays, as presented in section 1.0, was taken as primary reason to compare different interaction techniques (Mitchell, 2003). The interaction technique *Drag* was compared against *Corner* and *Wheel*. *Corner* was a well established technique used in many drawing applications, for example in CorelDraw (Corel, 2007). A more integral input would promise better results and would have more similarities with the manipulation of real world paper document on a table. *Drag* was invented to simulate this behavior better. *Wheel* was the third interaction technique, presented in Mitchell's study. The scroll-wheel of the mouse was used for rotation and could be seen as a 2 + 1 DOF instead of 3DOF (MacKenzie, Soukoreff & Pal, 1997). For a 30 degree rotation one wheel stroke with the finger is needed.

The circumstances of Mitchell's study, as for every study, are important. The study was performed using an indirect method, he used a LCD display (87 x 52 cm) laid flat on a desk. The participants were using a mouse, laid on the desk besides the display. The tasks were performed as a precise docking task with a precision of an 8 degree rotation. The target orientation was 30 and 90 degrees counterclockwise and a non-rotation situation. Two translation magnitudes of 0 cm and 37 cm were used, where the zero degree translation always had a rotation. The handles for *Corner* were fairly big, 5 cm squared.

Mitchell did not vary precision or handle size; he only varied interaction techniques (3), distance (2) and rotation (3). In total 100 trials per interaction technique were performed separated over 5 blocks. The first two blocks were eliminated due to the large change in mean completion time. The remaining 60 trials per interaction technique per participant represented skilled performance.

The main results of Mitchell's study showed that interaction technique *Drag* and *Wheel* did not perform as well as hypothesized (2003). Only on a 30 degrees rotation, *Wheel* was significantly faster. The integrated technique *Drag* performed slower than *Corner* on all the situations: translation, rotation (30 and 90 degrees) and the combined translation and translation tasks. Subjective workload measurements on the used interaction techniques showed the following order from the lowest to the highest workload: *Corner*, *Wheel* and *Drag*.

2.7. RNT versus Corner

Kruger performed an empirical study comparing a novel interaction technique Rotate 'N Translate versus *Corner* (2005). The *RNT* technique simultaneously rotates and translates a digital object using a single contact point. It has the behavior to rotate faster if the touch point gets closer to the document's center. A non-rotational region was added in the center of the document, sized 20% of document's width. Figure 3 presents the rotational behavior of *RNT* in action. When touching the document in the exact center of the width results in no rotation, if the line of movement is exactly upwards or downwards.

Kruger's study is important for this thesis, because it's results are used as a bases to draw this study upon. Kruger's study is mentioned in the first research question, see section 1.6.

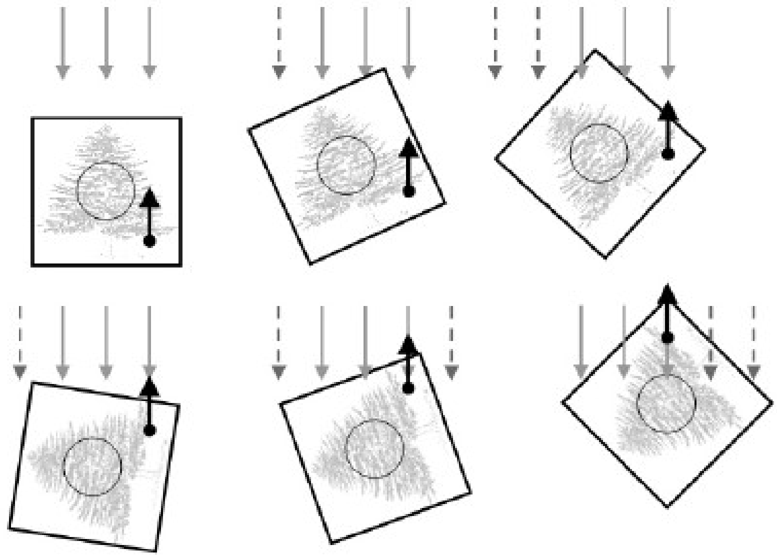

Figure 3: RNT: "Unbalanced movement resulting in upward translation and counterclockwise rotation from a control point located in the lower-right corner of the object", cited from Kruger (2005). Figure is taken from Kruger's paper as well.

Kruger performed his study using a SmartBoard DViT positioned horizontally. All the interaction was executed directly on the board using a stylus. The user study consisted of three parts:

1) a precise targeting task
2) a document passing task
3) a collaborative document passing task.

The first two tasks are the most interesting for this thesis, because this thesis describes two studies using similar conditions and also the results of the first two tasks of Kruger's study are used to compare against.

1) The precise targeting task consisted of 8 different positions positioned around the central start location. Sixteen orientations were used and the object that should be moved has a width of 13 cm and is squared. The target has a border of 1 cm at every side and defines the precision at an acceptable rotation offset of ±9.5 degrees. The target is placed at a distance of 27.6 cm. The results of these precise targeting tasks are that *RNT* is significantly faster than *Corner*. For *Corner* Kruger got 8.18 s (1.16 SD), for *RNT* 7.40 s (1.19 SD). Also remarkable is the high number of touches 3.67 (0.69 SD) for *Corner* and 1.34 (0.27 SD) for *RNT*. Mean movement times are high in comparison with the results of the studies described in this thesis; written in sections 4.2 and 6.2.

2) The document passing task shows similarities with Mitchell's, Kirkpatrick's studies: a less precise rotation to simulate real-world collaborative document passing. This document passing task has three target locations, two at a distance of 53.8 cm and one at 63.5 cm. The locations had their own orientation, 90 degrees, -90 degree and 180 degree rotation. The document passing task did not require a controlled accuracy. The only requirement was that the document brought to the target location should be readable for persons receiving the document. But there is nobody physically receiving the document at the target location. The participant who is moving the documents should make an assumption of the readability at the other's position. Results showed *RNT* is significantly faster than *Corner*. Mean movement time on RNT is 3.53 s (0.78 SD), for *Corner* 4.63 s (0.59 SD). The mean touches *RNT*: 1.18 (0.28 SD), *Corner*: 2.97 (0.57 SD). Note that for *Corner*, always two touches are needed to fulfill a rotation and translation. With *RNT*, it is possible to complete the whole task in one touch. A fixed minimal precision was not enforced in this task.

3) The collaborative document passing task was done using three participants doing a word puzzle. Distances were two 62 cm and one 75 cm. Participants receiving the word parts from others could reorient pieces themselves. Results only report about the amount of touches and a shorter touch distance. *RNT* has 2.99 (1.06 SD) touches and *Corner* 5.20 (1.04 SD). No movement times nor precision was measured by the software. Video analyses revealed an average final offset of 9.59 degrees for *Corner* and 13.25 degrees for *RNT*. Many of these offset angles (19.44%) were more than ±20 degrees.

All his tasks were performed using small handle size for *Corner*, 1.52 cm squared, 12% of the object's width. For *RNT*, the rotation-only circular region had a diameter of 2.53 cm, 20% of the object's width.

Indirect RNT versus Corner

In December 2005, Kirkpatrick, Atkins and Koster performed a user study with a LCD display laid flat at a desk (2006). Participants sat at a table and were using a Logitech PS/2 optical mouse. We compared *Corner*, *RNT* and *Drag*. Six target directions were used as well as three target orientations (-90, -30 and 30 degrees). The rectangle, 75% of the size of an American sheet of paper, was moved over a constant distance of 20 cm. The precision was set at ±15 degrees, meaning that the object is accepted with an offset rotation of 15 degrees clockwise or counterclockwise. Results of this study show mean movement times of 2.89 s for *Corner*, 3.54 s for *RNT* and 3.78 s for *Drag*; *Corner* is 22% faster than *RNT* and 31% faster than *Drag*. Acquisition times show means of 0.89 s for *Corner*, 1.36 s on *RNT* and 1.41 on Drag. The major improvement on the *Corner* average task time was a 50% shorter acquisition time.

Table 1 presents some study conditions of Mitchell's, Kirkpatrick's and Kruger's study. More details are explained in the earlier sections in this chapter. The target / document size ratio means the ratio between the target size and the document size; the targets are bigger. The last row of the table shows a ratio of the measured speed between the *Corner* and *RNT* techniques in the appropriate studies. It shows that Mitchell and Kirkpatrick found better performance on *Corner* while Kruger found *RNT* as the fastest technique. Several of the conditions between the studies, as presented in table 1, were different and likely influenced the study results. Section 1.5 explained this issue more extensively, while chapter 3 argues the detailed condition values of the first study.

Interaction Technique Conditions	**Mitchell (2003) Kirkpatrick et al., (2006)**	**Kruger et al., task 1 (2005)**	**Kruger et al., task 2 (2005)**
Target / Document size ratio	123%	127%	127%
Handle size	Large (5 cm / 29%)	Small	Small (1.52 cm / 12%)
Directness	Indirect	Direct	Direct
Device	Mouse	Stylus	Stylus
Distance	Mitchell: 37 cm, Kirkpatrick: 20 cm	27.6 cm	57 cm
Precision	±8°	± 9.5°	± 15°
Document size	17 x 22 cm	13 x 13 cm	13 x 13 cm
Target Orientation	Mitchell: 0°, -30°, -90° Kirkpatrick: -90°, -30°, 30°	0°, 22.5° ... 292.5° (16x)	-90°, -180°, 90°
Corner / RNT time ratio	Mitchell:0.92, Kirkp.:0.73	1.11	1.31

Table 1: Interaction Technique study conditions and performance

Directness and Integrality

As introduced in section 1.4, the interaction techniques supporting rotation and translation can be put into the integrality taxonomy, see figure 4. Mitchell already made a more sophisticated overview of interaction techniques visualized using the directness by integrality viewpoint (2003). He stated that interaction techniques using integral input and direct input are most desirable. Practical limitations as in technological drawbacks exist and limited the degrees of freedom that are actually used as input. He explored a part of the integrality versus directness space to reach insights on the assumption that a higher level of directness and more degrees of freedom would benefit the ease of use and speed of interaction techniques. The outcome of his study found the opposite, as explained in section 2.6. *Corner* was faster than *RNT*, while two years later Kruger found opposite results (2005). Thus, it still can be questioned why the taxonomy, as presented by Mitchell, did not became true in his results. Jacob's results suggest that the integral tabletop document rotation and translation tasks should be faster manipulated with an input device or technique that supports the same integral structure (1994). The *RNT* technique supports 2+1 DOF and mirrors the integral manipulation more than *Corner* supporting 1+1 DOF and should be faster.

This thesis investigates the deeper structure of the integrality taxonomy of tabletop interaction techniques but first needs to investigate into the conditions that confounded the results of the previous studies.

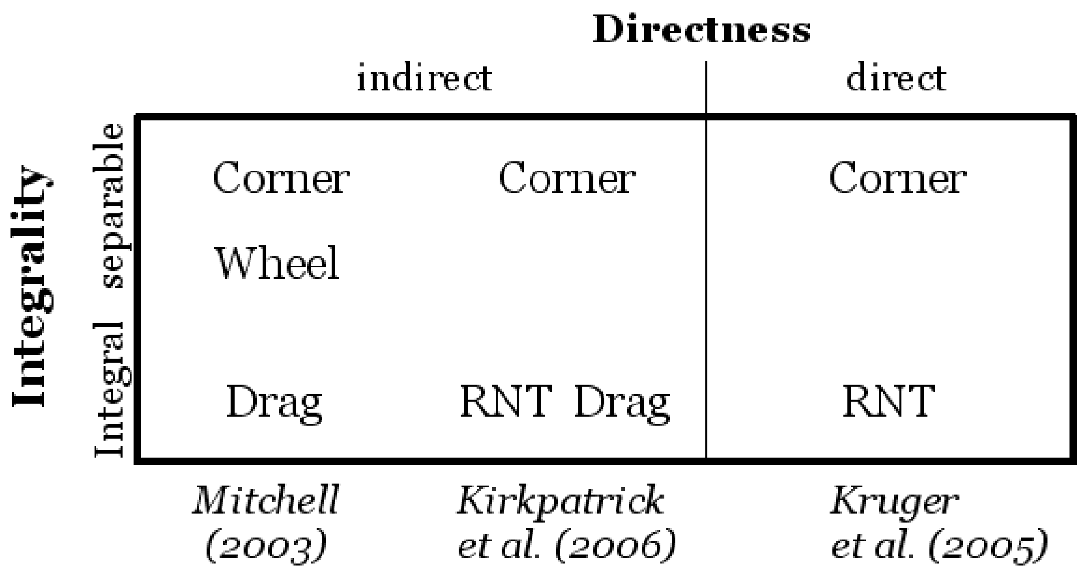

Figure 4: Comparing study spaces; directness and integrality.

3. Factors Influencing Tabletop Speed – Study 1

This chapter describes the design of the study investigating the factors that influence tabletop display performance in detail: movement distance, task precision and handle size. This study is also named as 'study 1'. The next chapter presents the results of this study.

3.1. Moving Documents on a Tabletop Display

Working with digital documents on a tabletop display consists of moving digital documents around and putting or keeping them in a readable position. In collaborative work, people would like to hand documents over to one another. Handing over documents comprises rotating and translating documents; by the sender or by the receiver of the document.

Tasks containing a translation and rotation movement of a digital document were created to measure performance. These tasks are movements from a start position to several different target positions on a tabletop display. Figure 5 presents, from left to right, the docking process included in every trial. The white square represents the digital document in a trial. The right position is the accepted state in which a trial is almost ended; the document is correctly aligned in the target position. The target's corners change color, from gray to yellow, if the correct corner of the document overlaps. The computer program measures how long it takes to position the digital document into the target position, until the aligned position is reached. Because the system needs to sense the position of the user's hand all the participants wore a glove containing LEDs.

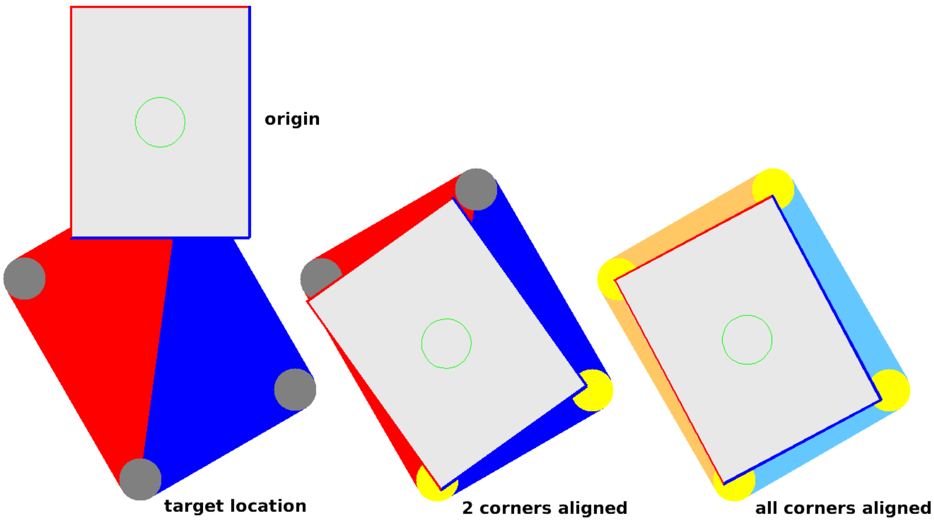

Figure 5: A typical trial. "left" position initial position, "middle" document almost aligned, "right" position document fully aligned.

Various factors that influence tabletop document usage were part of this study and therefore need some explanation how they were operationalized.

Precision

The precision factor expresses how accurate the document needs to be docked at the target position. The target position is drawn in figure 5 as the red blue rectangle and the size of the target is determined by the size of the circle shaped corners. The corners of the target location change the precision of the document docking. If the target's corners were very small, the document could only reach the accepted state if the corners of the document overlap the small corners of the target location. So the precision is directly influenced by the size of the target and its corners. The level of precision can be expressed in two different ways: using the size of the target corners or using the rotational degrees in which the document may differ from the orientation of the target. Both ways influence each other because big corners allow big angle differences. In the final state at figure 5, the document is not perfectly aligned though it is accepted. The intermediate state presents a non-accepted state because the two upper corners are not overlapping. If these target corners were a bit bigger they would automatically accept the difference in angle, because only then the corners were big enough.

Distance

The distance factor depicts the center to center distance between the document and target location. This factor influences the time needed to complete a document movement tasks, see Fitts' law and section 2.5.

As explained in section 3.5, the movement distances of 20 cm and 57 cm were chosen. Figure 6 presents four different positions with only two different distances. The lower two positions were included to avoid repetitive movements and fatiguing participants. These positions are not precisely mirroring the higher two positions but do have exactly the same distance from the start location.

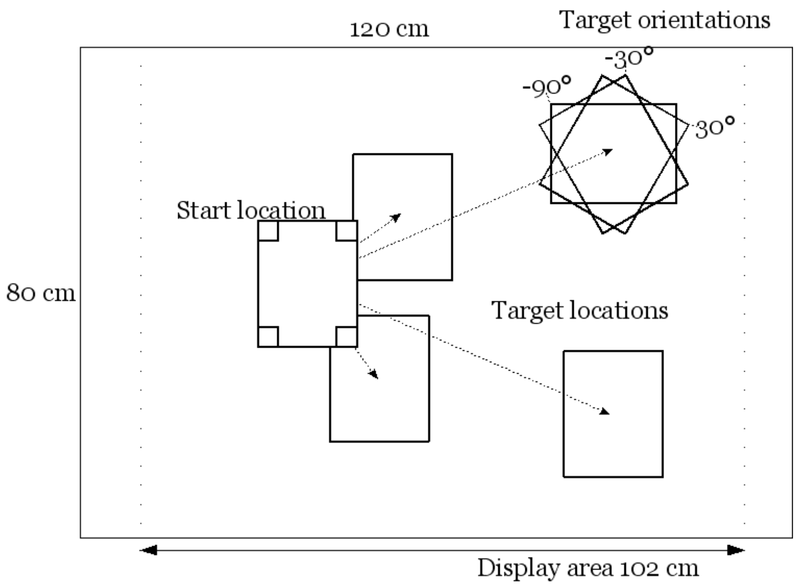

Figure 6: Tabletop set up

Handle size

The handle size factor stands for the varying handle sizes used in *Corner* and *RNT*. The handles presented in figure 7 present corners of 20, 35 and 50 mm, standing for small, medium and large sizes. These sizes were used in the study described in this chapter. Only one handle size is used per trial and every corner had the same size, when using the Corner interaction technique. Big handles can be reached faster than small handles, as a consequence of Fitts' law (see section 2.5).

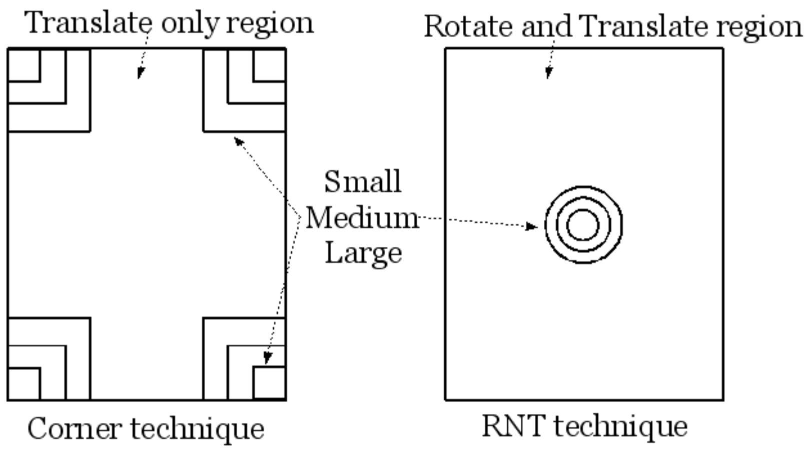

Figure 7: Handle sizes for Corner and RNT

Target orientation or rotation

The target locations may have a different angle than the document's start position. These different angles were varied to measure the effect of rotation. Figure 6 presents three different rotations at the upper right location as an example. The rotation of the target is referred to as orientation because it depicts the relation of the document within the target. Every target location could have such an orientation.

3.2. Precision and Movement Time

With digital document passing, the width of a target location is closely related with precision. Precise docking of the digital paper means a smaller target width compared with an imprecise docking task and therefore directly influences the movement time. But not only is the docking procedure a Fitts' task. There are multiple Fitts' tasks in one trial of moving the digital paper from a start to a target position. Let us show how a trial, using the *Corner* technique, can be seen in multiple Fitts' tasks, see figure 8. Task 1: the user's finger is starting at the middle of the table because the user just released the 'Start Trial' button and the trial has started. Next, the finger needs to go to the document with a certain width. Task 2: the finger with the document needs to go to the target position on a certain distance and the target position has a certain width. Task 3: if interaction technique *Corner* is used and a rotation is necessary the finger needs to release the document and aims to one of the four corners with a certain width. Task 4: the document needs to be aimed at the target with a certain rotation with a certain precision.

All these Fitts' tasks include a target's width and a movement distance. If a document would be moved in a trial with the *RNT* technique, Fitts'-like performance would happen. A *RNT* trial consists of aiming tasks as well as time to think which path to take. Acquisition time results in Kirkpatrick's study found that *RNT* took an average of 1.36 s while the *Corner* technique took 0.89 s (2006). These results suggest that for *RNT* the extra time was consumed by thinking about the right path (Kirkpatrick et al., 2006).

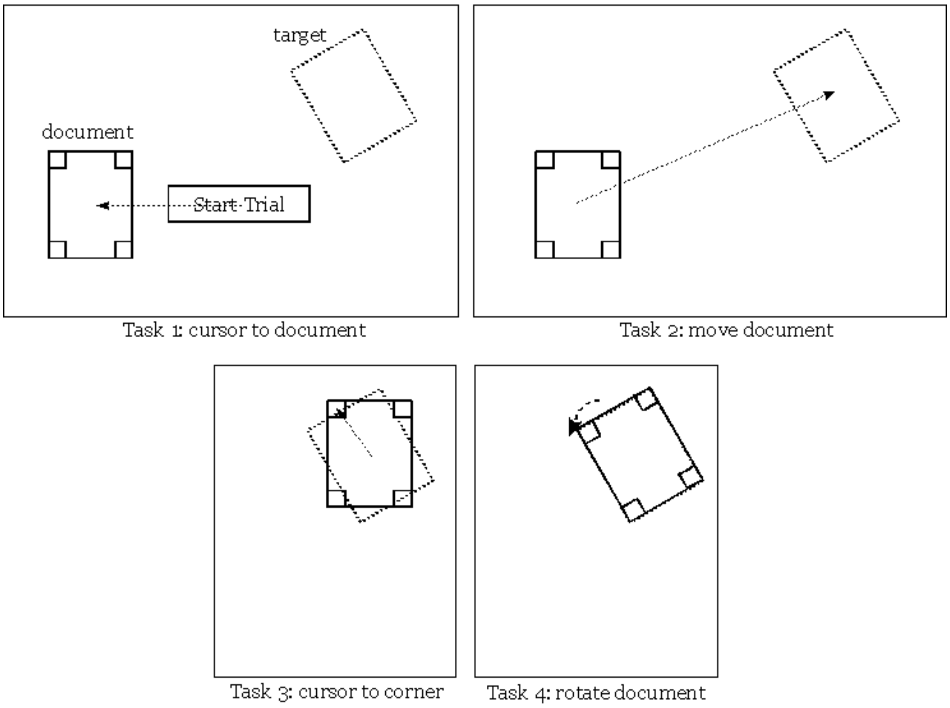

Figure 8: Fitts' law illustrated in a trial

Predicting movement times with the interaction technique *RNT* and Fitts' law is hard or even impossible because if a path with a curve is chosen, the document would be correctly aligned without the need of a final rotation. In other words, a longer path can be more efficient than the shortest because the rotation is adjusted along the way. The optimal path would not be the path as tested in Fitts' law because the optimal path is not a straight line. If the participants would choose straight line, a final rotation is necessary because every trial needs a rotation.

3.3. Performance Issues

This section presents the differences in performance found between the results of comparable user studies important for document passing tabletop applications. These studies only have a few different conditions worth comparing. The primary performance difference is that Kruger found that the *RNT* technique is 31% faster than the *Corner* technique whereas Mitchell found that a technique comparable to *RNT* called *Drag*, is 25% slower than *Corner* (on combined rotation and translation tasks) and Kirkpatrick found that *RNT* is 22% slower than *Corner*. Looking at the conditions that were used, not only the level of directness was different, also other conditions varied: movement distance, target orientation and handle size as the possibly influencing majors.

To enable comparing the results of this study to previous studies, it used the same conditions as Kruger's study, specifically task 2, 'document passing' (2005). Also the conditions of Kirkpatrick's study were replicated (2006). Kruger's study (2005) used direct interaction whereas studies from Mitchell (2003) and Kirkpatrick used indirect interaction (2006). This study used direct interaction because the similarity with Kruger's study. Direct interaction is also advantageous to achieve 'natural' interaction because of the absence of an additional device, such as a mouse. Also directness did not expect to have influence at the relative performance of *RNT* and *Corner*.

The research space of the study is presented in figure 9. The handle size (at the left vertical axis) is compared with precision (high precision means 11% and low precision means 21% of the document width) and distance (short and long: 20 cm and 57 cm). These values were derived from the Mitchell's and Kruger's studies, again to make sure the conditions are replicated. Every square with each two interaction techniques inside depicts a state with conditions which is included in the study. Note that directness is not visualized in figure 9.

The dashed gray lines express the predicted relative performance of interaction techniques *RNT* and *Corner* given the interaction conditions. They could be estimated because it is likely that every condition has an influence on performance. The continuous gray lines express the actual relative performance from the associated study.

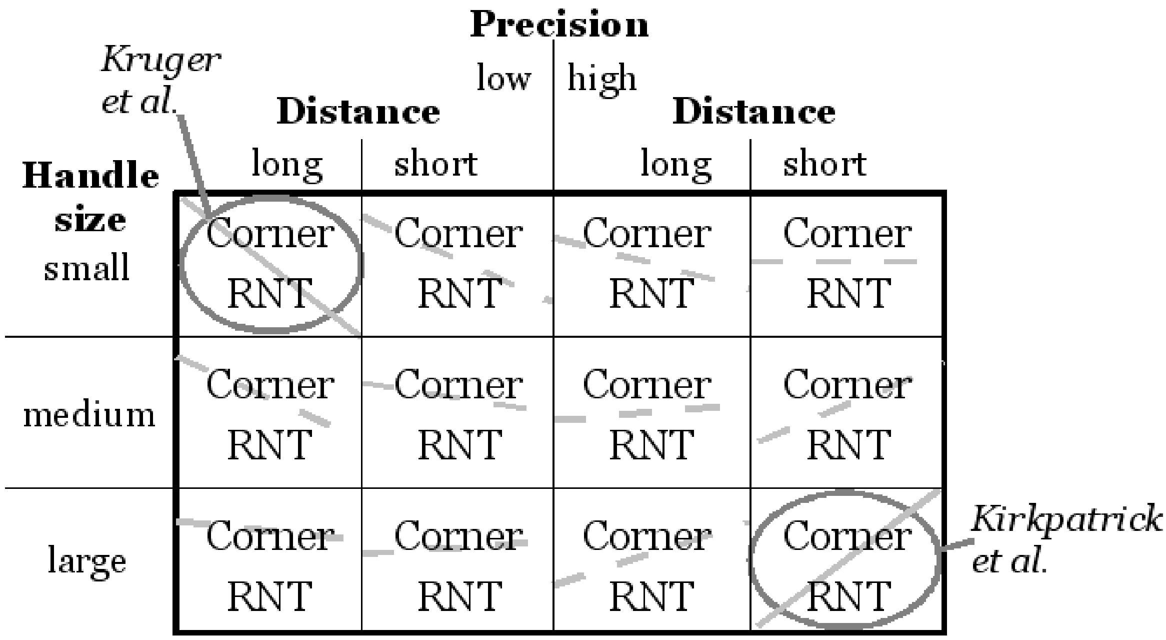

Figure 9: Handle size versus distance and precision

Figure 10 presents a zoomed-in upper left rectangle from figure 9, showing how the gray line should be interpreted with the extra information at the sides. The left side of the gray line inside the rectangle represents the presumed *RNT* performance and the right side *Corner*. Returning to figure 9, given this information the upper left rectangle (Kruger's study) shows a high performance on *RNT* and low on *Corner*; the lower right (Kirkpatrick's study) shows the opposite results.

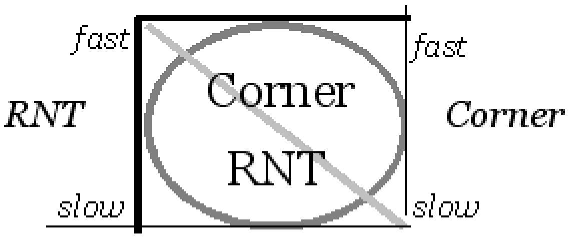

Figure 10: Zooming inside figure 9

The rectangles with the dark gray circles and use the relative performance from the previous studies, the others use predicted values. I expected the crossover effect to be replicated somewhere in the area between Kruger's and Kirkpatrick's study, because all the important variable conditions from the different studies were used.

Figure 11 and 12 present variations of figure 9 on expected performance of *RNT* and *Corner*, using the gray lines. These two figures indicate, in extreme, the possibility that results from previous studies are outliers. The conditions of the studies could cause worse performance on *Corner* or *RNT*. Figure 11 presents the possibility that *RNT* only performed very well on long distance, small handles and low precision and all the other conditions performing the opposite. Figure 12 presents the same idea, but for different conditions. These alternatives are not very likely, but illustrate the extreme conditions and possible consequences.

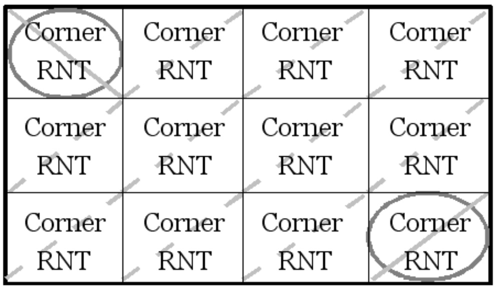

Figure 11: Alternative 1.

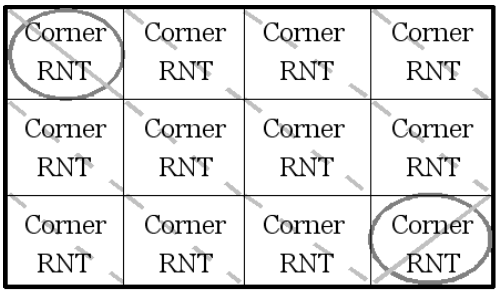

Figure 12: Alternative 2.

3.4. Research Questions and Hypotheses

The previous sections have explained details about the differences between the document passing studies on tabletop displays. This section describes the research questions for study 'Factors influencing tabletop speed' and the associated hypotheses. The research questions for this study are repeated from section 1.6.

Both research questions and hypotheses were used to define the study. The research questions specify the variables of interest, and the hypotheses specify the expectations about the relationships between those conditions.

> *Q1. What is the reason of the crossover effect in human performance as seen in Mitchell's and Kruger's tabletop display studies on document passing?*

Several factors likely influence tabletop interaction on document movement. As presented in section 2.6 and 2.7, at least three factors differ between those studies. Varying those three factors in this study is recommended to investigate into the influence size of the factors. It is without doubt that the factors actually influence speed. For example, doing document passing over a very short and very long distance will significantly differ in speed. The same reason counts for precision and handle size as well, but unknown is the size of influence. This user study therefore researched the following question by taking these factors into account.

> *Q2. What is the influence size of three factors: distance, precision and handle size on document passing?*

Hypotheses

Moving the document over the table has different effects depending on the interaction technique used. A longer distance in combination with *RNT* gives the document time to rotate over a certain distance. Longer distances probably will favor *RNT* more than is does on *Corner*. With *RNT*, the document's center and the touch point are trying to rotate towards the line of movement, see figure 3. For example, if you grab the document at the upper right corner and drag it to southeast, it will rotate in a way that the upper right corner will point to the southeast, given you have enough distance. While for shorter distances, extra movements are needed to achieve the necessary rotation, this influence relatively increases the time needed.

For *Corner*, the same rotation is always needed and the same effort is required. The rotation is unaffected by distance, so long as the location is physically reachable and not to far away. The *Corner* technique always needs two separate movements if both rotation and translation are involved. Here, the first movement does not influence the second movement. For *RNT*, the relationship between rotation and translation is tight; because they are influencing each other. For *RNT* counts that, if the distance is long enough, no further rotation is needed once the document reaches the target. Distance can only influence the first translational movement for *Corner*. This translation consists of separable actions, the user's hand first needs to point inside the document's area, which is a Fitts' task, see section 2.5 (MacKenzie et al., 1992). Then, the document is moved to the target with a coarse movement aiming and moving fast, ending in a more precise docking movement which relatively requires quite a bit of time. So, likely time and distance do not increase linearly, but unknown is how much extra time is needed when longer distances apply. The first hypothesis is:

> *H1. Movement distance has a bigger interaction effect on RNT than it has on Corner.*

Moving documents with an integrated technique as *RNT* can be quite fast in low precision situations. Especially if the distance is long enough, is it sufficient to make one coarse movement towards the target, while holding the document. The start touching point should be correctly chosen. In this situation, *Corner* suffers from two unavoidable separate movements. Having to switch handles adds overhead compared with *RNT*. By contrast, in high precision situations, *RNT* suffers from the integrated rotation and translation movements. If only a little document docking transition is needed, the document's rotation might also get influenced by the cursor movements. It is hard to make a translation only. The rotation and translation actions are separated in *Corner*, one can choose to modify one or another. The second hypothesis is:

> *H2. A low docking precision will favor RNT more than Corner.*

Corner and *RNT* differ in handle usage and the importance of the handles. The handles in *Corner* are always needed to make a rotation. For *RNT*, a handle is not needed to complete a combined rotation and translation. The handle is optional to help a rotational movement. If there is no handle using the *RNT* technique, the document will support really fast, almost incontrollable rotations if the document is touched near to the center. This is caused by the nature of *RNT*: it rotates the document by a calculation on the angle from the difference of the first mouse position and the second position from the document's center. If a document is touched very close to the center, the angle gets relatively high. So, adding the handle in the center prevents grabbing the document in a position where it is really hard to deal with it. Still, the question remains open if the users are interacting with the handle or not.

Rotations with *Corner* are likely hard to make if the handles are tiny. The cursor needs to be in the handle and this movement takes effort and time. According to Shannon's formulation of Fitts' law, movement time is determined by the log of the ratio of distance to width (MacKenzie et al., 1992). A quick calculation says that using a distance of for example 10 cm and a width of 2 cm or 4 cm takes an 30% decrease of movement time (smaller movement times are better). If big handles are used, for example when they are occupying 50% of the width of the document, the user does not have space to touch at the document for translational movements. Also, this movement is a Fitts' task and is influenced by changing the handle size. Since movements with *RNT* do not need an extra handle, and according to Fitts' law, the size of the corners influence the movement time towards a corner, it is likely that changing handle size from small to medium or big will influence Corner more than *RNT*. More information on Fitts' law is written in section 2.5. The third hypothesis is:

> *H3. Medium and big handle sizes will reduce movement time more for Corner than RNT.*

One could think of more hypotheses than these, as stated above. For example, that sitting will result in slower movement times as opposed to standing. The hypotheses used in this study were derived from the research questions and also reflect the most important predictions in this study. Results of the user study and reviews of the hypotheses are presented in section 4.3

3.5. Experimental Design

The study used a within-subjects design with three factors: document handle sizes (3 instances), movements distance (2 instances) and task precision (2 instances). Variation of target location is preferred to eliminate predictable locations. This helps to prevent tiredness of repetitive movements: two directions were used. Table 2 presents the used setup. Every factor multiplies the amount of trials (in one block) by the amount of variations of the factor. The order of direction, distance, handle size, target orientation, precision and interaction technique were counterbalanced and the participants were randomly assigned to an ordering, see appendix F for further details.

Factor	**Factors Influencing Tabletop Speed**	**Explanation**
Direction	2	NE, SE
Distance	2	20 cm, 57 cm
Target orientation	2	-30°, 30°
Handle size	3	Small, medium, large (20, 35, 50 mm)
Precision	2	8°, 15° (26, 46 mm)
Device	1	Finger
Directness	1	Direct interaction
Trials per condition	**48**	In one block.
Block	4	
Trials	**192**	
Interaction Techniques	2	Corner, RNT
Total Trials	**384**	(48 * 4 * 2)

Table 2: Setup of user study; trials and factors.

During the run of Kirkpatrick's study, an average trial took about 5 seconds to finish. The study involved filling in questionnaires and forms as well. Together it fitted within an hour, most taking about 50 minutes.

The precision values, also expressible as an allowed rotation if the document is located at the target's center, are originated from Kruger's study. In Kruger's study, the accepted rotation averages at ±11° and used for 81% of the trials. An accepted rotation greater than ±20° was used for the remaining 19% trials. In Kirkpatrick's study, a controlled orientation of ±8° is used. These values are the rotations accepted at the target position; the digital document may differ a plus and minus 8° from the exact target location. A bigger rotation will result in a non-accepting state. A precision of 11% of the document width is similar to 8° rotation. For this study an orientation of ±15° is chosen to ensure the crossover effect will happen by replicating Kruger's study conditions as accurately as possible. Note that Kruger did not enforce a precision and ±15° is approximating his condition. Table 3 presents the relation between the different studies. Note that target orientation represents the accepted rotation of the digital paper at the target position and does not represent the rotation of the digital paper at its start position.

Factor	Mitchell (2003)	Kirkpatrick et al. (2006)	Kruger et al., (2003), task 2	Study 1
Interaction techniques	Corner, Wheel, Drag	Corner, RNT, Drag	RNT, Corner	Corner, RNT
Document / Target ratio	123%	123%	127%	123%, 142%
Handle size	Large	Large	Small	Small, Medium, Large
Directness	Indirect	Indirect	Direct	Direct
Distance	37 cm	20 cm	57 cm	20 & 57 cm
Orientation	±8°	±8°	±15°	±8°, ±15°
Document size	17 x 22 cm	17 x 22 cm	13 x 13 cm	17 x 22 cm
Target orientation	0°, -30°, -90°	-90°, -30°, 30°	-90°, -180°, 90°	-30°, 30°

Table 3: Study conditions - a comparison.

RNT was chosen instead of *Drag* because the two were found to have equivalent performance (Kirkpatrick et al., 2005). A precise description of *Drag* is given in section 2.6.

3.6. Participants

Eight participants from the user study in December 2005 at SFU were willing to participate again (Kirkpatrick, 2006) . The December study had 20 participants. Because participants from the previous study had experience on both *RNT* and *Corner* interaction techniques, it was preferred to get the participants for this study out of the previous group. It is advantageous to get skilled performance on both interaction techniques, and almost everybody already has experience on *Corner* because this technique is well integrated into normal computer applications such as drawing programs. It helps to get comparable levels of skilled performance for the two techniques if the participants are familiar with *RNT* as well as on *Corner*.

A power analysis on the results from Kirkpatrick's study showed that a minimum of 6 participants were needed to replicate the crossover behavior (2006). Adding two more participants ensured this level of power would be met.

The ages ranged between 24 and 29 years old, with a median of 27 years and an average of 26.5 years. Two participants were female and six were male. All participants were SFU Computing Science graduate students.

Participant's computer and tabletop use

Every participant used a computer for more than 14 hours a week and used a mouse daily. Five participants reported to have a little experience in using rotating objects on a computer by dragging the corner, two participants use it regularly and one participant uses it daily. They never used a tabletop display, except for their participation in Kirkpatrick's user study (2006). All participants were right handed mouse users.

3.7. Protocol

Participants first read instructions about the ordering and contents of the user study and the sub tasks they were going to do, see appendix H for an example. They next signed a consent form describing the minimal risks associated with the experiment and reminding them that they could discontinue participation at any time. They then filled in a background questionnaire (see appendix I for an example), which amongst other questions asked whether the participant normally writes with the right or left hand. The questionnaire also asked the participants about their experience using direct touch tabletop displays and rotation of digital objects in for example art programs.

After the forms were filled in, the participant was guided to the experiment room. First, the experimenter demonstrated the technique once or twice by pointing where to touch the object and explaining how to move. Next, the participant could do the remaining six or seven practice trials. The practice trials consisted of in total eight target configurations, similar to the real trials in the study. To avoid unnecessarily precise docking, the experimenter demonstrated the minimum required precision to complete a trial. Because pilot studies had shown that most participants had considerable difficulty with the *RNT* techniques, we systematically trained them in a strategy. During the practice trials, the experimenter gave detailed advice on planning a move, including how to select a drag point and a drag path. The interaction part of the study was done standing.

After the 8 practice trials, participants performed four blocks of 48 trials using the same interaction technique and device. During these 48 trials, combinations of distance, precision and handle size were randomly varied, ensuring that each condition came by in every block. After the first four blocks were completed, the interaction technique changed and another four blocks were started. The order of interaction techniques was counterbalanced. The experimenter continued advising the participant in the first block out of four. If the participant had particular difficulty with a trial, the experimenter would ask them to return the document to its approximate starting point, and then indicate a better start contact point and path. In particularly challenging cases, the experimenter would demonstrate the path. These demonstrations only occurred in the first block, if at all. When the participant demonstrated consistently skilled performance, the experimenter left the room, closing the door to avoid disturbing the participant with noise from outside the experiment room. In every case, the last two blocks were done without any intervention from the experimenter.

Training was offered before every time participants started a new interaction technique. A training session for the *Corner* technique was offered, but no participant needed them, as they explained the experimenter. The experimenter specifically informed participants that for the *Corner* technique they could use either a translate-then-rotate strategy, or a rotate-then-translate strategy.

After each block, a dialog box recommended the participant to take a break of at most 30 s. Participants could end the break and start the next block whenever they wished. The four blocks for each interaction technique and device took 10-15 minutes to complete, including any breaks.

After every completed four blocks, participants completed a NASA Task Load Index (TLX) questionnaire (Hart & Staveland, 1988). The TLX scales were filled out on a Java program on a separate machine running in a different room. It took participants about 3 minutes to complete the this questionnaire.

After both combinations of blocks were completed and the TLX questionnaire was filled in, they filled in a paper with a preference ranking of interaction technique, *Corner* or *RNT*.

Total time for each technique, including practice and questionnaires, was 15-20 minutes. After both interaction techniques were completed, participants weighted the TLX dimensions (as given in appendix K), ranked the techniques by personal preference, and answered some open-ended questions (as given in appendix L) about their experience.

3.8. Equipment and Setup

The whole study is done at the Simon Fraser University located in Burnaby, BC. The study ran between June 15th and June 23rd 2006, during normal office hours.

A motion capture system was used (PTI Phoenix VZ4000) to record 3D coordinates with a precision of about 1 mm in at least 72 frames per second (Phoenix, 2006). Two trackers were used to decrease the chance of occlusion, see figure 13 for the physical setup. Both trackers were connected to the computer using two high speed serial ports. The indirect move area, at figure 13, should be ignored for this study.

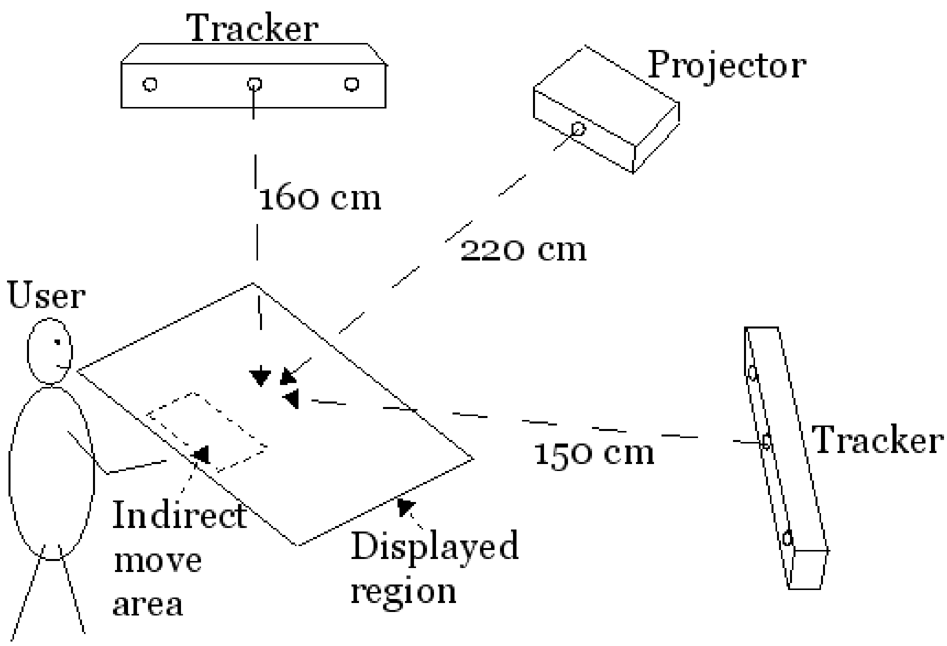

Figure 13: Tabletop display setup

The computer used was equipped with a graphics card fast enough to ensure frame rates above 60 fps: NVidia GeForce FX 5900 Ultra, with a resolution of 1280 x 1024 at 32 bit colors. The display view was cloned by the graphics card and sent to the projector. The computer contained an Intel Xeon dual-core, dual-CPU, at 2.80GHz using 2GB of internal memory. It could run the experimental software and the motion capture software without interrupting each other.

As operating system the computer ran Windows XP professional SP2.

The projector used is a Sony VPL-CX6, capable of creating 2000 ANSI lumen. It down sampled the resolution to fit the resolution of the graphics card into the physical maximum resolution of the projector: 1024 x 768 pixels. The down sampling caused a small decrease in readability of small fonts, but for the user study it did not matter because no small fonts or objects were used.

The experimental software was built using the newest Java SDK and toolkits available: Sun Java SDK 1.5.0_06.

Device

The study used a finger from a golf glove to interact with the tabletop, see figure 14. Two fingers from one glove were cut apart and only one finger was used per participant. Two fingers are needed due to differences in finger sizes of participants. The LED is located at 0.7 cm from end of the finger and positioned at the top. Cursor offsets for both medium and large fingers are the same because the LED is mounted at the same positions. The finger coverage was worn at the index finger. Medical tape was used to stick the coverage tight to the user's hand palm because a slipping glove-finger might cause imprecision.

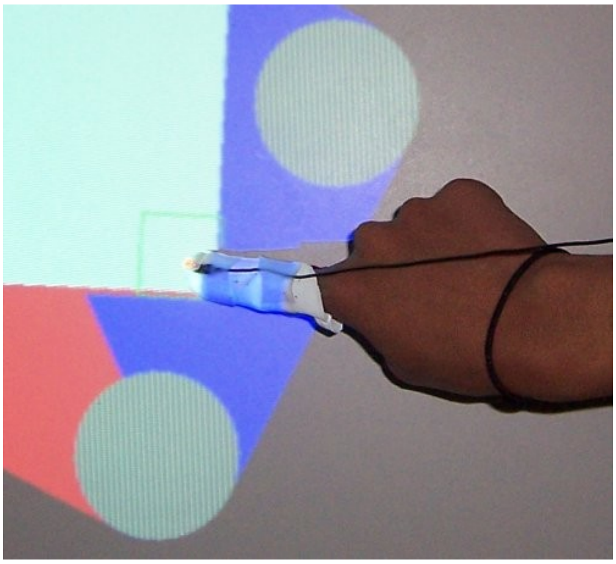

Figure 14: Completing a trail using the finger

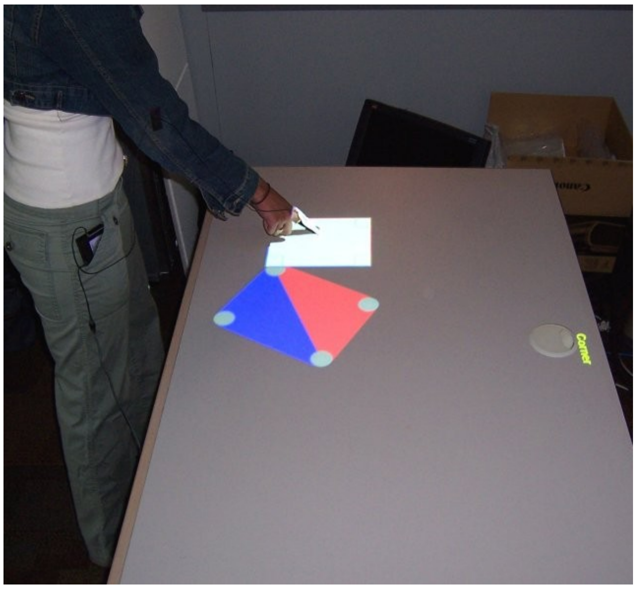

Figure 15: Using the tabletop with the user's finger.

The table was an ordinary office table. Its size is 120.0 x 80.0 cm; see figure 15 for an impression. The projector is located on the ceiling and pointing at the table, the actual screen size is 102 x 80 cm and centered horizontally on the table. That results in an offset from the left side of the table unto the screen start of 10 cm.

4. Factors Influencing Tabletop Speed – Results Study 1

This chapter presents the results of the first user study in detail, in particular the influence of different factors on tabletop interaction performance. At the first two sections the plain facts are presented and later, starting at section 4.3, the interpretation and discussion follow.

4.1. Data Cleaning

The experimental software sometimes recorded extra time between blocks and added it to the next trial. This unintentionally happened while participants were filling in questionnaires. Because of this bug in the experimental software, 3 trials were removed which took longer than 12 seconds.

Normal probability plots presented that the experiment data was skewed and contains substantial outliers. These 27 outliers were culled out, defined as any trial with a completion time greater than three standard deviations (6.70 s) from the mean.

In total 30 trials were removed out of 1536 trials from block 3 and 4, that is 1.95%. Blocks 1 and 2 were used to get skilled performance and practice participants; they were not used in the analysis.

4.2. Statistical Results

The average completion times and acquisition times are presented in figure 16. The upper gray line is the result of the *Corner* technique while the lower solid line depicts faster results for the *RNT* technique. The bars visualize the standard deviation on the completion times of the trials. For each couple, the left black faced one stands for *RNT* and the right gray faced bar stands for *Corner*. At the horizontal axes the 12 conditions are presented. All tested factors are listed in table 4 including their standard deviations and average acquisition times.

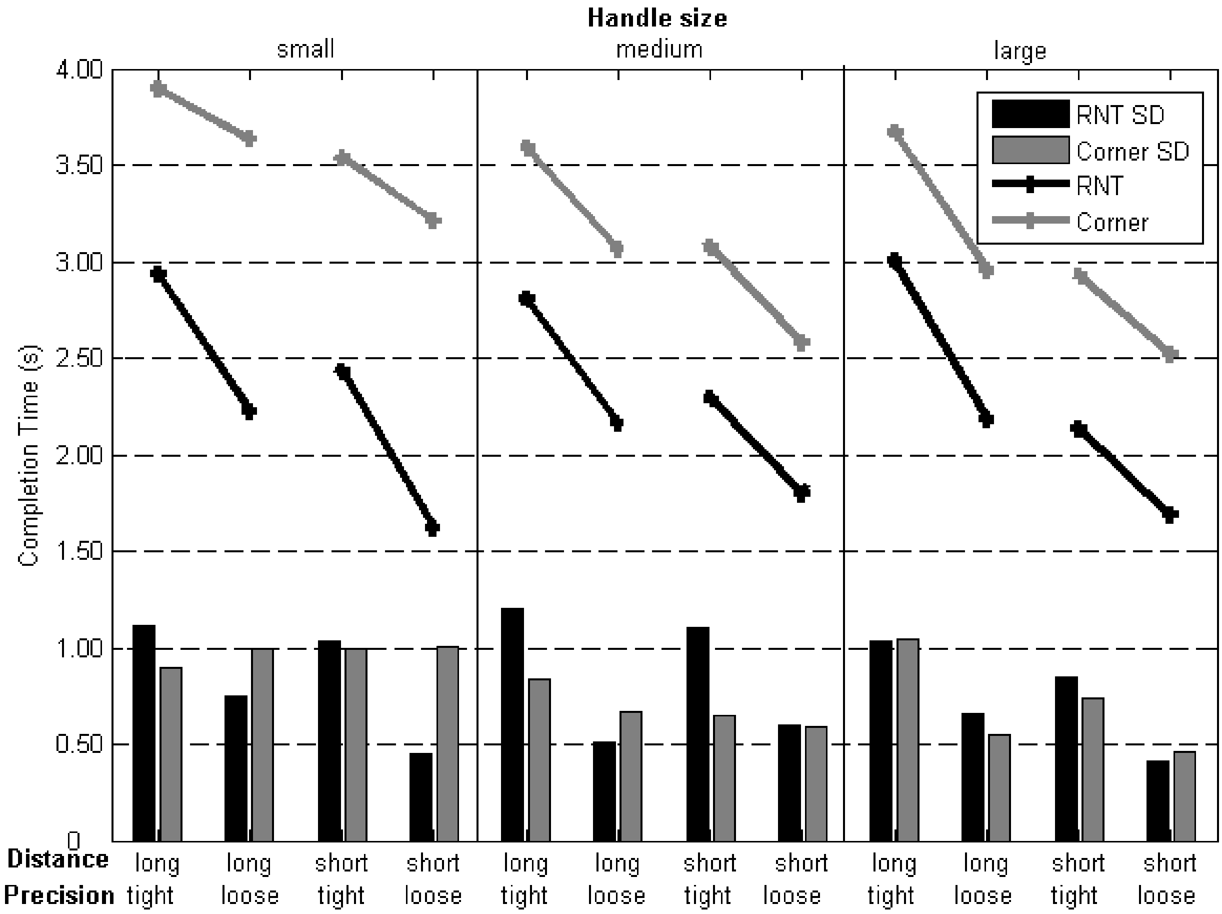

Figure 16: Average completion times (lines) with standard deviations (bars). The graph is split in 3 parts; by handle sizes: small, medium, large. Lines are movement times; bars are SDs.

The 'Condition found in study' column remarks the similar conditions used in this study and in Kruger's (2005) or Kirkpatrick's (2006). In other words, these completion times can be directly compared to theirs. Detailed results can be found in appendix A.

	Handle	Distance	Precision	Total	SD	Acq	Condition found in study
RNT	20	571	26	3.10	1.47	0.85	
	20	571	46	**2.22**	0.74	0.84	Kruger (task 2)
	20	202	26	**2.43**	1.04	0.85	Kruger (task 1)
	20	202	46	1.62	0.45	0.83	
	35	571	26	2.80	1.21	0.79	
	35	571	46	**2.16**	0.51	0.79	Kirkpatrick
	35	202	26	2.29	1.10	0.80	
	35	202	46	**1.80**	0.60	0.84	Study 2: Directness
	50	571	26	3.00	1.04	0.85	
	50	571	46	2.18	0.65	0.87	
	50	202	26	**2.14**	0.85	0.82	Kirkpatrick
	50	202	46	1.68	0.42	0.82	
Corner	20	571	26	4.24	1.46	0.71	
	20	571	46	**3.81**	1.25	0.75	Kruger (task 2)
	20	202	26	**3.81**	1.42	0.73	Kruger (task 1)
	20	202	46	3.30	1.24	0.71	
	35	571	26	3.74	1.16	0.71	
	35	571	46	**3.14**	0.89	0.69	Study 2
	35	202	26	3.07	0.65	0.75	
	35	202	46	**2.67**	0.96	0.72	Study 2
	50	571	26	3.81	1.29	0.72	
	50	571	46	2.95	0.55	0.71	
	50	202	26	**3.01**	0.97	0.75	Kirkpatrick
	50	202	46	2.52	0.46	0.77	

Table 4: Average completion, SD and acquisition times (time in seconds, size in mm)

Significance tests

The result data was analyzed using the repeated-measures analyses of variance. ANOVA assumes a normal distribution of the data sets and therefore a quantile-normal plot was taken. The plot indicated that the data sets were skewed and had substantial outliers. Plots of the log-times did not show these problems, so all statistical tests were performed on the log of the times. The Mauchly sphericity test was far from significant ($p = 0.100$ and higher), therefore we used the unadjusted degrees of freedom in the analysis of variance.

The significant effects ($\alpha = .05$) are written in table 5, the study had 8 participants ($N=8$).

The main effect of handle was significant. Only the small handle size was significantly different from the large handles ($p = 0.004$). The medium versus small ($p = 0.064$), or medium versus large ($p = 1.0$) handles did not show to be significant.

Effect	Variable		Effect Size	CI	Significance	df
Main	Interaction Technique		47%	[37%, 57%]	0.000	7
	Handle				0.001	14
		Small – Medium	8%	[0%, 18%]		
		Small – Large	10%	[4%, 16%]		
		Medium – Large	1%	[-4%, 6%]		
	Distance		22%	[18%, 27%]	0.000	7
	Precision		22%	[18%, 26%]	0.000	7
Two-way	Interaction Technique * Precision				0.003	7
	Interaction Technique * Handle size				0.005	14
Three-way	Interaction Technique * Handle * Precision				0.008	14
	Handle * Distance * Precision				0.049	14

Table 5: statistical figures: effect size, confidence interval, significance, degree of freedom

4.3. Hypotheses Evaluated

This section describes the results of the first study using the hypotheses.

H1. Movement distance has a bigger interaction effect on RNT than it has on Corner.

A two-way interaction effect between movement distance and interaction technique was not significant (p = 0.069). Table 6 presents the average task completion times for each interaction technique and distance. The task completion time difference between the long and short distance is essentially the same as for both techniques; the relative difference is 0.03 seconds. This hypothesis was not confirmed.

	Distance	Total	Difference
RNT	Short	1.99	
	Long	2.58	0.58
Corner	Short	3.06	
	Long	3.62	0.55

Table 6: Task time: movement distance and interaction technique.

H2. A low docking precision will favor RNT more than Corner.

A two-way interaction effect between precision and interaction technique was significant (p = 0.003). Table 7 presents the average task completion times for each interaction technique and task precision. *RNT* is favored more than *Corner* by choosing a low precision task. The task completion time difference between the high and low precision is larger at the *RNT* technique (0.68 s) as oppose to *Corner* (0.55 s). The relative differences is 0.13 seconds. This hypothesis was verified.

	Precision	Total	Difference
RNT	High	2.63	
	Low	1.94	0.68
Corner	High	3.61	
	Low	3.07	0.55

Table 7: Task time: Precision and interaction technique

H3. Medium and big handle sizes will reduce movement time more for Corner than RNT.

A two-way interaction effect between handle size and interaction technique was significant (p = 0.003). Table 8 presents the average task completion times for each interaction technique and handle size. One can see that *RNT* was not favored much by changing the handle size but *Corner* did show a bigger difference. Big handles decreased the average task time with 80 ms compared with medium handles. Bigger effects were measured between the small corners and both medium and large corners (640 ms or 720 ms difference). If one would remove the small handles from the ANOVA test, handle size would not be tested significant nor would a two-way interaction between handle size and interaction technique be significant. Medium and big handles helped *Corner* more than *RNT*. This hypothesis was confirmed.

	Handle	Total	Difference	
RNT	Small	2.35	0.09	Small – Medium
	Medium	2.26	0.01	Medium – Large
	Large	2.25	0.10	Small – Large
Corner	Small	3.79	0.64	Small – Medium
	Medium	3.15	0.08	Medium – Large
	Large	3.07	0.72	Small – Large

Table 8: Task time: Handle size and Interaction Technique

4.4. Workload Results

To measure workload of parts of the study, participants filled out a NASA task load index (TLX) workload ranking after completing all blocks for a given technique (Hart & Staveland, 1988).

The result data was analyzed using the repeated-measures analyses of variance. Results of the TLX ranking did not show significant results (p=0.922, 7 df). Table 9 presents the average and standard deviation per interaction technique. *Corner* and *RNT* resulted very similar, with *Corner* having a larger standard deviation.

TLX results	Corner	RNT
Average	40	41
SD	20	15

Table 9: TLX Workload results

4.5. Questionnaires

All participants filled in a background questionnaire prior to the study, a questionnaire with questions about each interaction technique and a short preference ranking questionnaire after the study. This section summarizes the outcomes.

Participant's comments

Participants pointed out that *Corner* is easier and more straightforward than *RNT*. They disliked having to click twice and the two necessary steps of rotation and translation. For *RNT*, they liked to do the task in a single click and one participant said that it was more instinctive because he could think less. Other participants disliked the extra mental demand and said *RNT* was harder to align the document.

In the general comments section, two participants pointed out that the small corners were difficult; one participant said that bending the neck and back was physically uncomfortable; two participants thought that *RNT* would be preferred after more practice. Appendix G presents all the participant's feedback and comments.

Ranking

Preference ranking showed that 5 participants preferred *RNT* and 3 participants *Corner*.

4.6. Discussion

The major result of this study is that movement distance, handle size and docking precision could not put *Corner* before *RNT* being faster in document passing tasks. The *Corner* technique is found slower than the *RNT* technique in every condition.

Kirkpatrick's study found different results (2006). They showed that the *Corner* technique is faster than *RNT* using indirect tabletop interaction. If one would compare the results of this study to Kruger's Task 1, remarkable results are visible (2005). Kruger's study task 1 presented relatively slow movement times at the precise targeting task compared to this study. The task conditions are similar. This study used a distance of 20.2 cm while Kruger used a similar, a bit longer distance of 27.6 cm; a part of this study used a precision of ±8 degrees while Kruger used ±9.5 degrees. This study also used the direct interaction situation, with the user's finger and a mounted LED on top. Kruger used direct interaction as well but with a stylus. A detailed description of Kruger's study can be found in section 2.7; appendix A has the detailed results of this study. Kruger's movement times are averaging at 7.40 s (1.19 SD) for *RNT*, and 8.18 s (1.16 SD) for *Corner*. Using the same conditions, this study got with *RNT* 3.10 s (1.47 SD) and on *Corner* 4.2 s (1.46 SD). This is roughly twice as fast. The relatively slow task times for Kruger's study, task 1, is likely caused by the combination of a small document and a high precision.

The interaction technique *RNT* was much faster than *Corner*. The estimated improvement was 47%. The short distance task (20 cm) was 22% faster than the long distance task (57 cm). Loose precision was 22% faster than tight precision.

There was a significant interaction effect between precision and interaction technique. Precision had a bigger effect on *RNT* than on *Corner*. In high precision situations it might be beneficial to adjust only one degree of freedom, using a separated interaction technique. Using *RNT*, precise adjustments can always influence the document's rotation and translation unnecessarily.

The subjective workload results did not find remarkable results; the averages did not differ significantly.

The questionnaires pointed out that the small corners on the *Corner* technique were difficult for some users. Small surfaces (small width) are in general harder to hit, compared to bigger surfaces (large width), consider Fitts' law in section 2.5. Also, the accuracy of the motion capture system likely made it harder to do precise movements. This especially became visible using the small corners with the *Corner* technique.

These high precisions should be avoided in combination with the accuracy of the motion capture system. The two-way interaction effect with interaction technique and handle size was caused by the small handles. Section 7.2 has more details about the estimated accuracy of the motion capture system.

The results of this study leads to a next study, because it is not clear why the crossover effect could not be reached. The hypotheses for the next study are stated in section 5.2.

5. Device and Directness – Study 2

This chapter describes the study investigating the influence of Device and Directness on tabletop speed in detail. This chapter starts with an introduction and the following section explains the set up and protocol. The results are explained in the next chapter.

5.1. No Crossover Effect yet

After the first study 'Factors influencing tabletop speed' was completed, it was possible to predict the relative performance of *RNT* and *Corner*, given the values of the investigated factors handle size, distance and precision. But one problem was not solved, as written in section 4.6: the crossover effect was not re-created and research question Q1 remained unanswered.

> *Q1. What is the reason of the crossover effect in human performance as seen in Mitchell's and Kruger's tabletop display studies on document passing?*

This study 'Device and Directness' investigated the influence of some factors not tested in the previous study.

Kruger's, Mitchell's and Kirkpatrick's studies were using different levels of directness and different devices. There was no study known that compared different levels of directness directly to each other, on tabletop display interfaces. The same is true for devices. It could be possible that these factors that were not compared in the first study, have a major influence on performance, in a way that they could speedup *RNT* and slow down *Corner*. Since the first study was performed, it was clear that distance, precision and handle size could not influence performance that much, because the crossover effect was not achieved for these parameters.

Figure 17 present two levels of directness as well as the devices used in this study. Also the setup overlaps with previous studies is presented, drawn with the gray eclipses. The first study used the user's finger for the direct conditions, in both *RNT* and *Corner* interaction techniques.

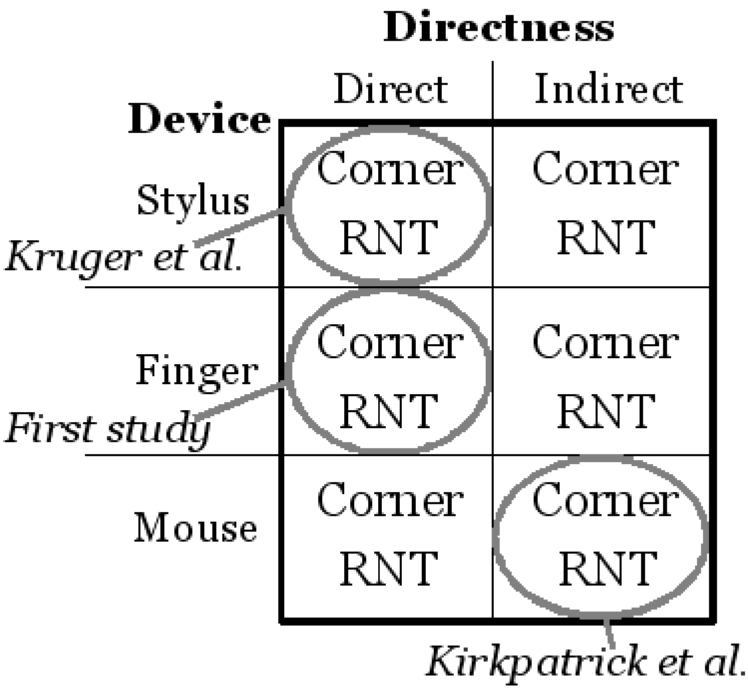

Figure 17: Levels of directness and different devices.

The 'Device and Directness' study used a mini-space area, representing the whole workspace of the tabletop display, as indirect condition. The upper left location in the mini-space represents the upper left location of the tabletop display. Figure 18 presents a stylus with the tabletop display, currently using this mini-space setup or the inset condition. The white rectangle depicts the digital paper to be moved to the target position: the red blue rectangle with the four bright circles. The inset area is bounded and marked by dark blue lines. The blue lines were clearly visible while using the tabletop display. Kirkpatrick's study used a mouse besides the LCD workspace, which isn't actually an inset condition but can be compared with the inset condition in this study, because the workspace and the display are different.

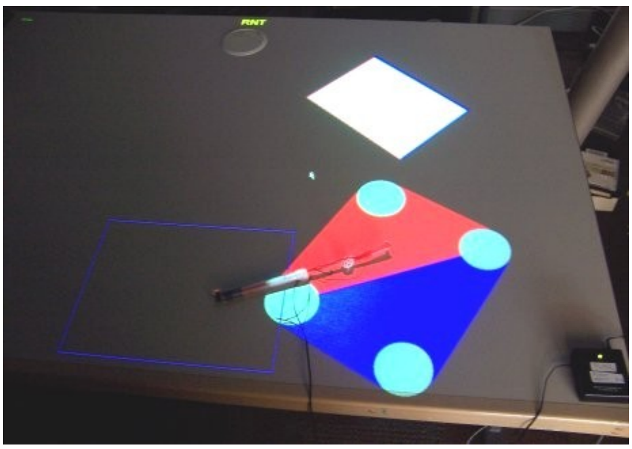

Figure 18: Stylus using the inset condition

The stylus device works similar as a pen, users can operate the stylus by pointing and touching the tabletop display. The finger device was the same as used in the previous study. The mouse device is a normal wireless mouse, but modified by taping a LED to it, to capture its position on the table. The mouse became an absolute pointing device by ignoring the normal mouse coordinates and using the absolute coordinates received from the motion capture system.

5.2. Hypotheses

The first study 'Factors influencing tabletop speed' tried to answer the first research question. This question was about the reason behind the crossover effect, as written in section 1.6. The factors influencing performance on tabletop interaction (distance, precision and handle sizes) were investigated. This study could therefore focus at other factors: directness and device. The predicted influence of directness and device are included in the following hypotheses.

Both the index finger and thumb control a stylus. This likely will achieve a higher precision because of the better control and the smaller tip compared to the mouse or finger. This improved precision might result in a better docking precision and improve the task speed. The first hypothesis of this study is as follows:

> *H1. The stylus will perform faster than the finger and mouse.*

Previous studies using the indirect situation found better results on *Corner* (Kirkpatrick et al., 2006; Mitchell, 2003). The first study 'Factors influencing tabletop speed' found that *RNT* was faster in the direct situation. Since the factors investigated in this study could not cause *Corner* to be faster than *RNT* in the direct situation, it is likely that directness or the device caused the crossover effect. The second hypothesis is as follows:

> *H2. In the indirect situation, Corner will perform faster than RNT.*

Because the large fingertip's size, it is assumed that in high precision situations, the finger will perform slower than the stylus. The indirect situation requires a higher precision than the direct situation, given the digital workspace is similar sized, but the physical working area is smaller. This hypothesis assumes that using the stylus results in a higher precision. The third hypothesis is as follows:

> *H3. In the indirect situation, finger will perform slower than the stylus.*

Results of the test of the hypotheses are presented in section 6.3.

5.3. Experimental Design

The experiment used a mixed-effect design: one between-subjects condition (directness) and five within-subjects conditions (direction, distance, target orientation, device, interaction technique).

To prevent carry-over effects between the direct and inset condition, the directness factor was kept constant per participant. Fifty percent of the participants got the indirect situation with the inset displayed at the table. The remaining part got the direct situation, where the whole table was used to interact. The order of device and the order of technique were counterbalanced in each group.

Several conditions were varied in this study, and two were investigated to see their influence: device (3 instances), directness (2 instances).

Three different devices were used, a mouse, a stylus and the user's own finger.

Both direct and indirect conditions were used, where the indirect condition was created using the inset condition.

Other factors were varied and not part of the research are: distance (2 instances), direction (2 instances) and target orientation (3 instances). These were varied to avoid predictable movements, to avoid fatiguing and to mirror the previous research conditions.

Both small and long distances were used again to represent a broad range of circumstances.

The target orientation added a -90° degree rotation, compared to the previous study. This was needed to assure that rotation did not affect the results and also mirrors Kirkpatrick's study and Mitchell's study better. The previously used -30° and 30° were still included.

This study reused the values on handle size and precision from the first study. Reusing these values makes this study easily comparable to the previous study, but also to other studies, as described in section 2.7 and chapter 3.

Medium size of handles was used because participants of the previous study showed to have no problems with medium sized handles and larger handles did not improve performance much.

The low precision value, associated with a ±15° degree rotational freedom, was used because more precise values were not needed for document passing tasks and this value is also associated with the previous study and therefore allows comparing.

The target sizes are directly deduced from the precision factor; lower precision requires bigger target circles (at the corners) and bigger targets to fit these circles, see figure 5 in section 3.1 to clarify this.

The size of the study prevented that every condition could be tested by the same participant. To prevent fatiguing participants, a typical session could be no longer than an hour in total. The order of interaction technique, distance, target orientation and device were counterbalanced and the participants were randomly assigned to an ordering. Table 10 presents the details of the chosen factors.

Factor	**Study 2**	**Explanation**
Direction	2	NE, SE
Target orientation	3	-30°, 30°, -90°
Handle size	1	Medium (35 mm)
Precision	1	±15°
Trials per condition	**12**	In one block, per participant
Block	4	
Device	3	Stylus, Finger, Mouse
Interaction Technique	2	Corner, RNT
Total Trials	**288**	Trials per participant
Directness	2	Direct / Indirect

Table 10: Setup of 'Device and Directness' study; trials and conditions

Because the workload measure of the 'Factors influencing tabletop speed' study did not show significant differences, the results of this measure were not used in this study. Table 11 presents an overview of conditions from important past studies and in the current study.

Study Factor	Mitchell (2003), Kirkpatrick (2006)	Kruger et al. (2003), task 2	Study Factors Influencing Tabletop Speed	Study Device and Directness
Target size	123%	127%	123%, 142%	142%
Handle size	Large	Small	Small, Medium, Large	Medium
Directness	Indirect	Direct	Direct	Direct & Indirect
Device	Mouse	Stylus	Finger	Stylus, Finger, Mouse
Distance	Mitch:37 cm, Kirk:20 cm	57 cm	20 & 57 cm	20 & 57 cm
Precision	±8°	±15°	±8°, ±15°	±15°
Document size	17 x 22 cm	13 x 13 cm	17 x 22 cm	17 x 22 cm
Target orientation	Mitchell: 0°, -30°, -90° Kirkpatrick:-90°, -30°, 30°	-90°, -180°, 90°	-30°, 30°	-30°, 30°, -90°

Table 11:Study conditions - a comparison.

5.4. Task

The tasks performed by the participants were equal to the tasks performed in the first study, described in section 3.1.

5.5. Participants

A total of 18 participants conducted the study. Their median age was 26 years and averaged at 26.9 years. All participants were students from Simon Fraser University. They did not participate in the first study. Two or three participants participated in Kirkpatrick's study using a mouse besides a flat monitor. Kirkpatrick's study ran 6 months earlier and did not use any of these devices and did not use direct interactions.

At first, participants were invited by sending an email to the computing science graduate student email list. This group did not supply enough students so more students were asked to participate.

The direct group consisted of 6 male and 3 female participants. Their ages ranged between 23 and 38 years. The median age was 27 years and the average was 29 years. All 9 participants of the direct group were right handed in controlling the mouse and writing. Seven computing science graduate students participated and two other participants were from other disciplines.

The indirect group consisted of 5 male and 4 female students. Their ages ranged between 19 and 33 years. The median age was 25 years and the average was 24.9 years. All 9 participants of the indirect group were right handed in controlling the mouse, but one participant writes with the left hand and normally controls the mouse with the right hand. Because participant number 14 used a hand controlled wheelchair, we chose to put him in the indirect group, so that this participant could reach the whole working space. The participant was not hindered by its seating during the study. The indirect group consists of 7 computing science graduate students and 2 undergraduates from other disciplines. The counterbalanced order and distribution of directness, interaction technique and interaction device is presented in appendix F.

All but one participant used a computer for more than 14 hours in a week, and used a mouse daily. Participants reported to have used rotation and translation a little or not regularly. Participants were using a tabletop display almost never; three participants a little; one regularly and one every week.

5.6. Protocol

Participants first read instructions about the ordering and contents of the user study and the sub tasks they were going to do, see appendix H. They next signed a consent form describing the minimal risks associated with the experiment and informing them that they could discontinue participation at any time. They then filled in a background questionnaire (see appendix I), which amongst other questions asked whether the participant used the mouse with the right or left hand. Due to the devices used and hardware calibrations done for this study, only participants using the mouse with the right hand were invited. This questionnaire also asked the participants about their experience using direct touch tabletop displays and rotation of digital objects in for example art programs. During the questionnaires the participant was seated.

After the forms were filled in, the participant was guided to the experiment room. First, the experimenter demonstrated the technique once or twice by pointing where to touch the object and explaining how to move. Next, the participant could do the remaining six or seven practice trials. The practice trials consisted of in total eight target configurations, similar to the real trials in the study. To avoid unnecessarily precise docking, the experimenter demonstrated the minimum required precision to complete a trial. Because pilot studies had shown that most participants had considerable difficulty with the *RNT* techniques, we systematically trained them in a strategy. During the practice trials, the experimenter gave detailed advice on planning a move, including how to select a drag point and a drag path. The interaction part of the study was done standing.

After the 8 practice trials, participants performed four blocks of 12 trials using a given interaction technique and device. The experimenter continued advising the participant in the first block. If the participant had particular difficulty with a trial, the experimenter would ask them to return the document to its approximate starting point, and then indicate a better start contact point and path. In particularly challenging cases, the experimenter would demonstrate the path. These demonstrations only occurred in the first block, if at all. When the participant demonstrated consistently skilled performance, the experimenter left the room. In every case, the last two blocks were done without any intervention from the experimenter.

Training was offered before every time participants started a new combination of interaction technique and device. The training session for the *Corner* technique was offered, but no participant needed them. The experimenter specifically informed participants that for the *Corner* technique they could use either a translate-then-rotate strategy, or a rotate-then-translate strategy.

After each block, a dialog box recommended the participant to take a break of at most 30 s. Participants could end the break and start the next block whenever they wished. The four blocks for each interaction technique and device took 6-9 minutes to complete, including any breaks.

After the four blocks were completed for a device/technique combination, participants completed a TLX questionnaire. The TLX scales were filled out on a Java program on a separate machine running in a different room. It took participants about 3 minutes to complete the TLX questionnaire.

Total time for each technique and device, including practice and questionnaires, was 9-12 minutes. After all combinations of interaction techniques and devices were completed, participants weighted the TLX dimensions (see appendix K), ranked the techniques by personal preference, and answered some open-ended questions (see appendix L) about their experience. Maximum session time was 1 hour and 15 minutes, with most taking about 55 minutes.

5.7. Equipment and Setup

The whole study was done at the Simon Fraser University located in Burnaby, BC, Canada. The study ran between July 25th and July 28th 2006, during normal office hours.

Three different kinds of devices were used, see figure 19. The two fingers from the golf glove as used in study 'Factors influencing tabletop speed' are with them.

The stylus device is 25 cm long and contains two LEDs. The 1st LED is positioned at 0.5 cm from tip. The 2nd LED is positioned at 25 cm from the tip. Both LEDs were attached to the stylus with tape to hold them in place properly. The pen used to build a stylus was made longer than an ordinary pen. The 2nd LED was used in combination with the 1st LED, giving 3D coordinates back to the computer. The 3D data was used to calculate where the exact tip of the stylus should be. It is impossible to place the first LED precisely at the tip, due to the size of the LED. A calculation of a line in 3D space was used to determine the start position of the stylus and the software cursor is drawn at appropriate location.

The mouse was a *Logitech Cordless Optical Mouse*, with a scroll wheel. A single LED was centrally mounted just above the mouse. This position was needed to avoid occlusion. The mouse had a width of 6.5 cm. To make the LED better visible to the user, a software offset or dislocation of the cursor of 1.5 cm was needed. This dislocation was shifted towards the top of the mouse, see figure 19.

During the inset condition, a blue rectangle, with a width of 2 pixels, was displayed 55 cm from the top of the table, see figure 20. This rectangle was approximating the center of the table. The inset had a width of 28 cm and a height of 22 cm. The table's height was 74 cm during both user studies.

All other details on the implementation of this study are equal to the first user study and therefore don't need to be repeated.

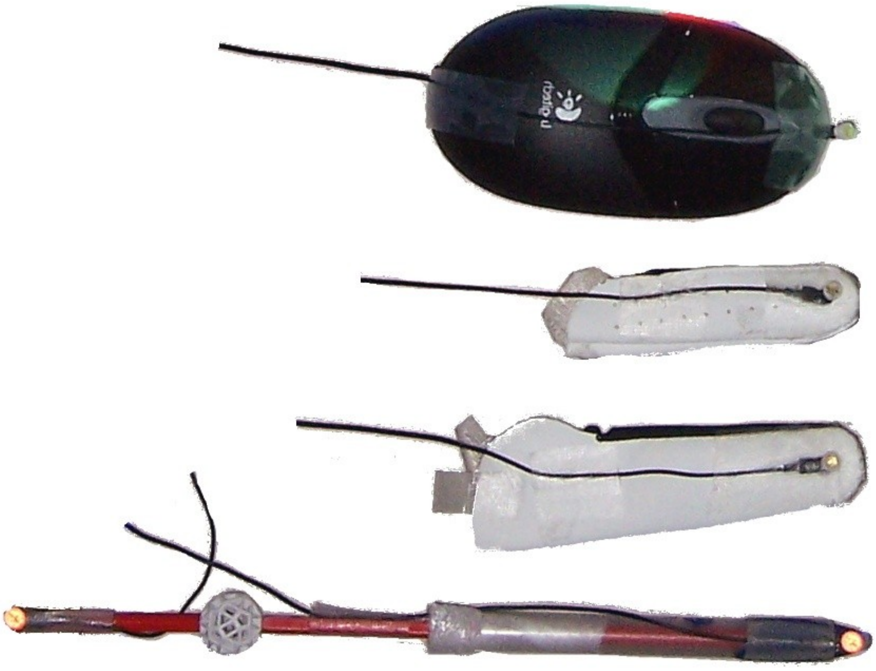

Figure 19: Devices: Mouse, glove fingers and stylus. Two finger sizes were used to fit small and big hands.

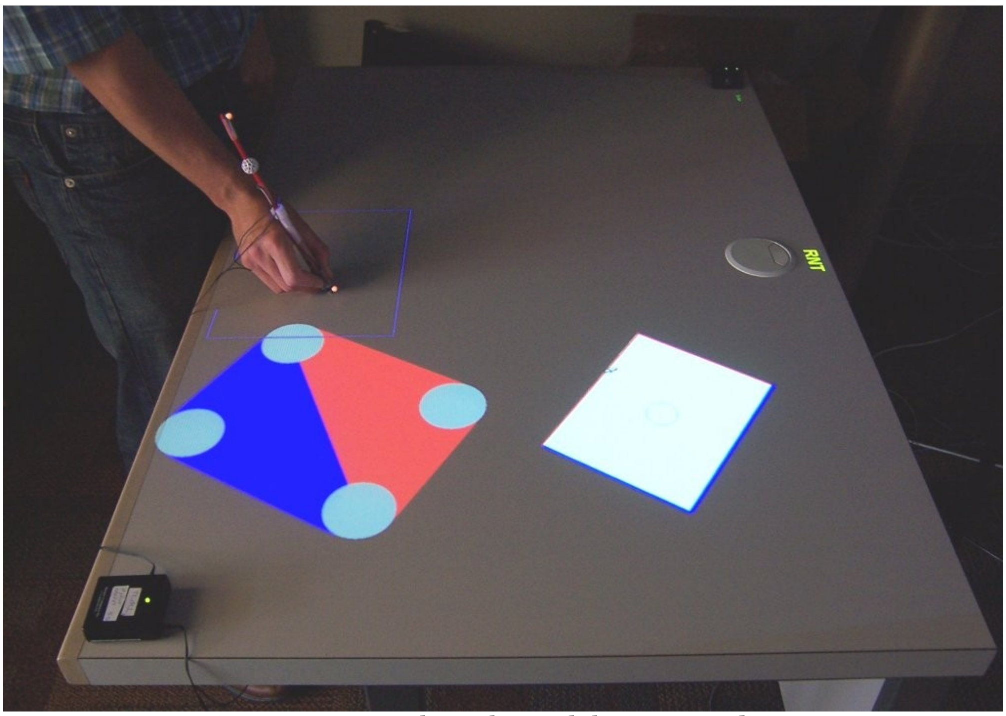

Figure 20: Using the stylus and the inset condition.

6. Device and Directness – Results Study 2

Two types of data were collected during the execution of the study. The first type is summary information at the end of every trial of both the practice and normal blocks, used for the main analyzes; the second type consists of path data, used for accuracy measurements and optional path analyzes.

In detail, the first type contains the following data: the phase of study, current block number, sequence number of trial, absolute start time in Unix time stamp format, current interaction technique, device used, space (direct or indirect), document x and y coordinates, target x and y coordinates, target angle in degrees, target corner precision radius, corner size in mm, translate-only of interaction technique *RNT* in mm, visual offset x and y coordinates, trial completion time in ms, document acquisition time in ms, document docking time in ms, number of clicks of the device's first button, distance in ms between document start position and target (center to center) and a handle counter to see how often the handles are used.

The second type contains: the path data of the document and used device was recorded. These were stored in a separate file. The path data contain on every sample: time stamp in ms, current document x and y coordinates, current device x, y and z coordinates, current button or touch status, depending on application. The motion capture system was operating in 3D mode. This was used to record and use the height of the device.

6.1. Data Cleaning

The experimental software sometimes recorded extra time between blocks and added it to the next trial. This unintentionally happened while participants were filling in questionnaires. Because of this bug in the experimental software, 9 trials were removed which took longer than 12 seconds. Normally, a trial is ended in five seconds or less.

Due to strange recordings of the experimental software some trials were completed in less than one second, even under 100 ms.. This is physically speaking not possible, and therefore we removed 4 trials that ended surprisingly quickly. The likely cause is the software timer or experimental software communication errors between the server and client.

Normal probability plots presented that the experiment data was skewed and contained substantial outliers. Plots of the log-times did not show these problems, so all statistical tests were performed on the log of the times.

These 30 outliers were culled out, defined as any trial with a completion time greater than three standard deviations (9.0 s) from the mean.

In total 43 trials were removed out of 2608 trials from block 3 and 4, that is 1.65%. The first two blocks were used to approach skilled performance and to practice participants; they were not used in the analysis. Appendix D presents two box plot figures with performance per block, per interaction technique.

6.2. Statistical Results

Only block 3 and 4 were used, since they are indicators of skilled performance, see appendix D for the performance figure, per block. Participants' mean total, acquisition, and dock times were computed for the 24 trials in these two last blocks.

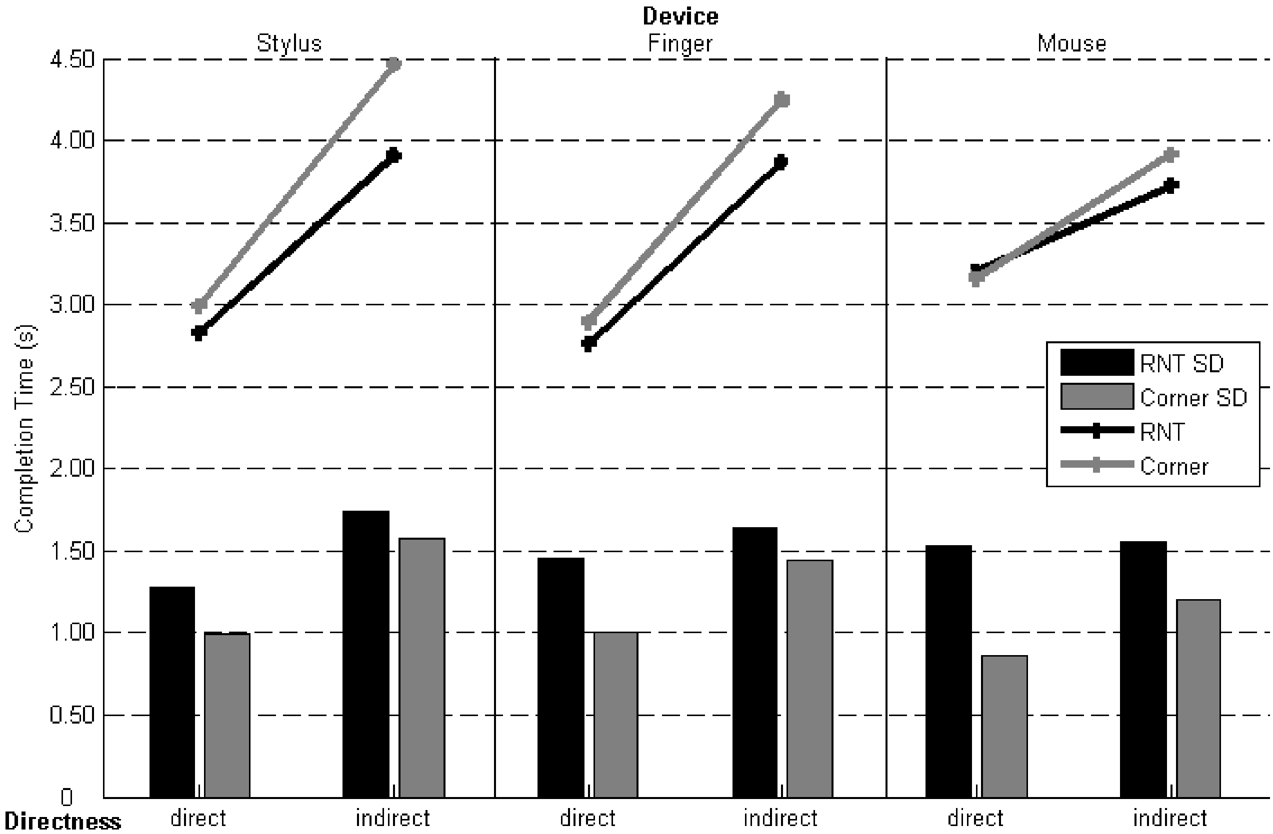

Figure 21: Average movement times by device, directness and interaction technique (lines) and standard deviations (bars). Appendix B presents detailed values.

Figure 21 presents the average movement times by device, directness and interaction techniques. Direct was 36% faster than indirect: direct 2.97 s and indirect 4.02 s. The individual participant's completion times and averages by several different conditions (table 18) are presented in appendix C.

Significance tests

The data result were, similar to the first study, analyzed using the repeated-measures analyses of variance. See section 4.2 for the detailed description.

The Mauchly sphericity test was far from significant ($p = 0.525$), therefore we used the unadjusted degrees of freedom in the analysis of variance ($\alpha = .05$).

Table 12 presents results of the analyses of variance. Note that device was not significant.

Effect	Variable	Effect Size	CI	Significance	df
Main	Interaction Technique	11%	[5%, 18%]	0.002	16
	Directness	36%	[14%, 60%]	0.001	16
	Device			0.580	32
	Stylus – Finger	3%	[-9%, 16%]		
	Mouse- Stylus	1%	[-8%, 11%]		
	Mouse – Finger	4%	[-6%, 15%]		
Two-way	Device * Directness			0.044	15
	Interaction Technique * Directness			0.393	16

Table 12: statistical figures: effect size, confidence interval, significance, degrees of freedom

The direct condition had a major estimated influence of 36%. The direct condition was faster on all the tested situations.

RNT was the fastest technique over the whole study. *RNT* showed an improvement of 11%. Only on the direct mouse situation interaction technique *Corner* was faster.

The two-way interaction effect between device and directness showed that mouse was influenced the least; directness had twice as much influence on the stylus and finger.

The two-way interaction effect between Interaction Technique and Directness was not significant.

6.3. Hypotheses Evaluated

This section describes the results of the second study using the hypotheses.

H1. The stylus will perform faster than the finger and mouse.

The stylus did not perform as fast as predicted. The average movement times are for stylus 3.36 s, finger 3.31 s and 3.46 s for mouse. These results do not differ significantly. Table 18 presents the detailed results. It can be speculated that either using the stylus did not offer better precision or the expected improved pointing precision with the stylus did not have impact on the movement time. The latter issue is described in section 7.2. This hypothesis was not confirmed.

H2. In the indirect situation, Corner will perform faster than RNT.

Corner did not perform faster than *RNT* in any of the indirect situations (see figure 21). The average movement times on the indirect situations are 4.20 s for *Corner* and 3.83 s for *RNT*. There was no significant interaction effect between directness and interaction technique. The next chapter continues on this issue. This hypothesis was not confirmed.

H3. In the indirect situation, finger will perform slower than the stylus.

The results for the indirect situation by device are: stylus 3.91 s, finger 3.87 s and mouse 3.72 s. As the results show, finger is faster than the stylus, though not significantly. The mouse is even faster than the finger. As well as at H1, the sensing accuracy could have influenced the speed of the stylus negatively or the stylus could not offer better precision by itself. This hypothesis was not confirmed.

6.4. Workload Results

The TLX data was analyzed using the repeated-measures analyses of variance. Direct input had significantly lower workload than the indirect condition (p=0.007, 16 df). Device and interaction technique did not present significant output. Only rankings are presented in this section.

Table 13 presents the average TLX scores and standard deviations by device and interaction technique. A higher value means a higher workload.

The direct input situation had a 40% lower workload compared to indirect CI [13%, 68%], 16 df); TLX values average at 24 for direct, and 40 for indirect. The direct situation The finger contributes most to a low workload ranking. The average score of *RNT* is 33 and for *Corner* 31 (non significant); stylus averages at 35, finger at 28 and mouse at 34 (non significant).

		Stylus		Finger		Mouse		
		RNT	Corner	RNT	Corner	RNT	Corner	Average
Direct	**Average**	27	25	20	18	32	23	**24**
	SD	14	18	9	13	16	15	**14**
Indirect	**Average**	45	43	34	39	44	38	**40**
	SD	20	25	17	19	20	17	**20**

Table 13: TLX workload ranking by device and interaction technique; averages and standard deviations.

6.5. Questionnaires

All participants filled in a short preference ranking questionnaire after the study. This section summarizes the outcome.

The questionnaires reported that the lower right position at the tabletop display was harder to control than the other three positions; see section 7.3 for the explanation.

The direct situation participants said that the stylus was easy to grab, share and use, but it was sometimes harder to use because they needed to lift the stylus higher than they thought it needed. The mouse was easy to grab by hand and they were used to a mouse. As a disadvantage, they reported the mouse as a clunky device and slow. The finger was easy and fast to use; accurate and excellent control. As a disadvantage, they said that it was tiresome to work for a long time; and it was sweaty to use. On the interaction techniques, they commented that *RNT* gets better after training. *Corner* has less mental demand. A general comment from the direct group was an idea to simulate weight (momentum) for the digital paper.

The indirect situation participants commented that the stylus was easy to use and similar to writing. One participant did not like to keep the pen upright. The mouse was bulky to use and was not comfortable by one participant. Another participant reported that it needed no adaptation time. The finger was very natural, and a participant said to have more control and that it was easier and faster to pick up. Some reported the finger to be too sensitive and another reported a load at the arm and wrist. On the interaction techniques, they commented that *RNT* was tedious and that they needed to get used to it; others added that it would improve after some time. A general comment was that they liked the inset space better than a touch pad, because it was bigger.

Appendix G presents all the participant's feedback and comments.

Ranking of devices and interaction technique

A preference ranking for every device and both interaction techniques was filled in separately. Table 14 presents the outcome. *RNT* was preferred by 10 participants out of 18. The finger device was preferred the far most, especially in the direct situation. The mouse was the least preferred device, 11 participants placed the mouse last.

	Corner		RNT			Stylus		Finger		Mouse	
	Indirect	Direct	Indirect	Direct		Indirect	Direct	Indirect	Direct	Indirect	Direct
Rank 1	4	4	5	5		2	2	5	7	2	0
Rank 2	5	5	4	4		3	5	3	2	3	2
Rank 3						4	2	1	0	4	7

Table 14: Two separate subjective preference rankings: interaction techniques (left) and devices (right)

7. Discussion

The crossover effect powered both studies on combined document rotation and translation. The crossover effect did not get re-created in both studies.

The first study showed that *RNT* was faster in every tested condition, using direct interaction. The size of the interaction technique handles, task precision and movement distance did have an influence on *Corner*, but this could not achieve that *Corner* performed faster than *RNT*. The second study showed that *RNT* was faster in all tested conditions except if the mouse was used in the direct condition, where the two were equivalent. Direct interaction was 36% faster than indirect and device did not influence performance significantly.

It was not possible to isolate the directness factor without changing other factors, such as size of actual movement or visual offset, as well. The results therefore only apply to situations where directness is varied together with a visual offset change in combination with a changed size of actual movement. A situation where these conditions are not changed together is rare; indirect interaction forces to have a visual offset, but does not force to have a changed size of movement.

It was expected that the separable interaction technique, *Corner*, would perform faster than the integrated technique, *RNT*, using the indirect situation (see sections 5.2 and 6.3). Especially when the mouse was used in the indirect situation, the studies of Mitchell (2003) or Kirkpatrick (2006) found faster results on *Corner* using similar conditions. It raises the question why *Corner* did not perform as fast.

Mouse usage

An important difference is the use of the indirect mouse in this study, compared to the use of a regular indirect mouse in Mitchell's or Kirkpatrick's studies. If one holds a regular mouse, the control point is located underneath the center of the hand. The control point of a mouse is the location of where it senses the x and y movements on the table's surface. In the 'Device and Directness' study, the sensor input (the motion capture LED) was positioned at the top of the mouse, see figure 19. The offset of the control point might have influenced interaction because rotary wrist movements have different control over the cursor's movements. It is not clear if the offset of control point influences integrated interaction techniques more than separated interaction techniques.

A regular high precision optical mouse was used in Kirkpatrick's study, where *Corner* performed better than *RNT*. The imprecision of the motion capture system configuration, in the indirect situation, as explained in section 7.2, might also have caused *Corner* to perform slower because *Corner* needs two movements: a rotation and a translation. Both movements need to have the required precision. When the mouse is less precise, it takes more time to do two separate movements including a handle switch.

Integrality

Both studies found that the more integral technique, *RNT*, performed better than the separable technique *Corner*. These interaction techniques are the only techniques tested from these integral and separable classes. The two studies showed that a higher form of integrality on the interaction technique improves performance on integral document rotation and translation tasks. Techniques that are even more integral than *RNT*, such as *Two Point* (see section 1.4), might even perform better.

Workload

Both studies did not present significant differences in workload between the integral and separable technique. Therefore, it can not be concluded that more integral techniques also lower the workload.

The second study found a significant interaction effect on the workload of directness: direct interaction should be chosen to decrease the workload. The workload of the indirect situations of study 'Device and Directness' was almost as high as workload values of the direct situation of the first study. It can not be concluded that the first study was as hard as the indirect situation of the second study due to the non-significance of the workload values and the different study conditions.

Other considerations

There are a few other considerations that should be taken into account. Some factors could influence the results and bias the performance of the conditions tested. The next section argues about the standing position of the studies. Next, the accuracy of the devices used and the accuracy information from the user study path files are presented.

7.1. Standing or Sitting

Participants were standing during both studies instead of sitting. Standing would benefit the larger, direct movements because it is easier to reach farther. Sitting would benefit smaller, indirect movements because the arm could rest at the table and one could experience more control. More physical effort is required while standing and making small movements.

Using the mouse as an absolute device was done to test the effects of hand posture and device mass. Using the mouse in an absolute way kept other factors constant, such as movement distance and precision. The mouse results should not be considered as representative mouse performance. Using a mouse at a relative way would enable comparing the mouse to other previous studies (Kirkpatrick et al., 2006; Mitchell, 2003), but would disable measuring hand posture and device mass effects.

7.2. Accuracy

If the measured cursor point position differed from the user's expected cursor point, an inaccuracy did occur. This might have affected the results. There are three sources of inaccuracy. First, the sources of accuracy are described and later the estimates of the effects of the sources are given.

Firstly, due to the sensing technology of the motion capture systems and the used LEDs at the user's hand or device, the system had an upper bound accuracy of approximately 2 mm.

Secondly, the LEDs also caused an inaccuracy because the area where the light was emitted, was wider than a square millimeter. Even if the motion capture system would be able to sense more precise movements, the beam of light itself would cause an imprecision in some situations.

Thirdly, the experimental software updates every input data by intervals, as the path files show. Intervals 15 ms are quite common in these path files. These intervals come done to 66 samples per second. This section continues to estimate the effects of these sources of inaccuracy.

The first source of inaccuracy, the sensing accuracy of 2 mm includes both fixed offset and momentary fluctuation of position. For the direct situation, the level of accuracy is good enough, because all the movable objects on the tabletop display are big enough. It did not hinder the acquisition and docking procedures. In the indirect situation, a 2 mm accuracy gives an enlarged imprecision on the table. Because the 280 x 220 mm inset area corresponds with a 1020 x 800 mm full tabletop area, a 2 mm move on the inset area results in a 9.2 mm move on the full tabletop area. For the direct situation, it is hard to make acquisition errors caused by the inaccuracy of the system; all the acquisition positions (document, corners or circular region inside document) were fairly large. For the indirect situation, the 2 mm inaccuracy enlarged to a 9.2 mm inaccuracy could have made a precise docking task, or a precise pointing task harder. This might have slowed down the performance on indirect interaction.

The path data files with the digital document path and cursor path were recorded during the user studies. Figure 22 presents the cursor interval for the indirect situation. Looking at the tall bars, it illustrates that every sensed millimeter in the input space corresponds with about 4.5 pixels in the output space (tabletop display). The most occurring intervals were 1, 4, 5, 9, 14 pixels. That argues that the sensor precision of the captured LED positions at the motion capture system is about 1 mm. A 1 mm move stands for 4.5 pixels at the tabletop display, in the indirect situation. The sensor precision is not the only factor that limits the overall precision; therefore, also the second and third sources of inaccuracy should be taken into account.

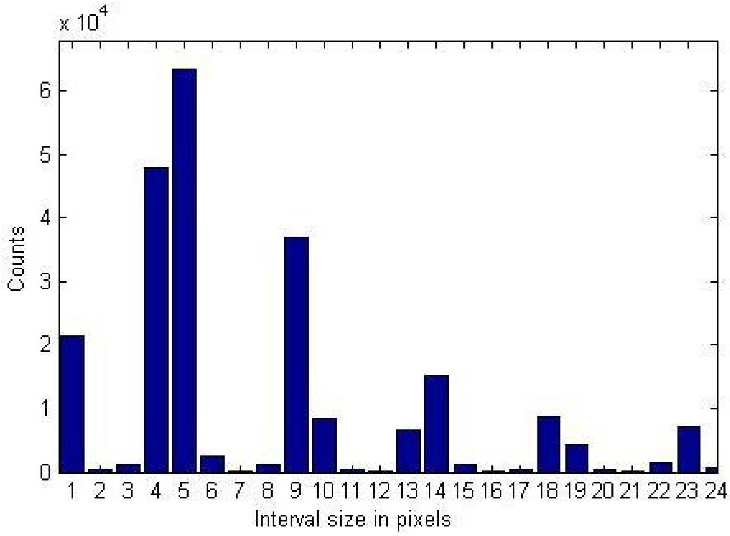

Figure 22: Cursor interval sizes for the indirect situation

The second source of inaccuracy was caused by the size of the LEDs. The area where the light was emitted, was wider than a square millimeter. Even if the motion capture system would be able to sense more precise movements, the beam of light itself would cause an imprecision in some situations. This became clear when a calculation of length was done between two static LEDs on the stylus, in a test situation. According to measurements of the motion capture system, the length between the two static points varied between 6 cm and 6.8 cm, while rotating the stylus away from the motion capture system, increasing the angle between the two points and the capture system. The actual points did not move on the stylus, but they were captured as if they moved. The motion capture system calculates the center of the visible LED region, but a wider beam of light makes it harder to calculate the center if the angles of the LEDs vary. The capture system can not detect rotation of the LEDs themselves, but calculates the position of the LED using the 2D visible light beam.

The third source of inaccuracy was caused by the temporal sampling coarseness. The path files of do not contain data of every millisecond but intervals of 15 ms are quite common. The sensing resolution of the indirect situations were between 5 and 10 pixels, that is between 1 and 2 mm on the table. The 1 pixel moves are not actual moves but likely an outcome of rounding, because movements smaller than 1 mm could not be sensed and 1 mm move corresponds with 4.5 pixels and because 4.5 pixels in the output space results in a ±4 or a ±5 pixel difference.

In general, the inaccuracy had mostly impact on the docking procedures, because fine movements were only needed during the docking procedure. Due to the imprecision, it was a bit harder to fine dock the digital document inside the target, especially in the high precision situations. It also depended on the precision of the participants themselves: sometimes they were approaching the target near the center position, so it did not care because a minor correction was not needed. In a few cases, when participants were approaching the final target position, and the participant did a few tiny corrections to the current position of the document, the coarseness played a negative role. Important to mention is the fact that participants did not always acquire the digital document on the edge, but instead they chose a position around, or for example 2 cm away from the edges. Acquiring a document at the edges increases the chance of pointing off the document and makes moving the document more sensitive to inaccuracies. Because participants mostly did acquire a document away from the edge, the imprecision likely did not influence the 'pointing at the document' part of a movement task. The appendix contain two graphs (figure 26 and figure 27 at page 63) presenting the initial document contact points.

These three sources of inaccuracy, likely have affected performance negatively in some conditions. In the indirect situation, inaccuracy made precise movements harder and possibly increased the performance differences between the direct and indirect situations. This might have increased the effect size of directness. The frequent use of the *Corner* handles and the size of the handles were likely affecting *Corner* more than *RNT* in the indirect situation, since the *RNT* handles were not frequently used. It is expected that a more accurate input system can not solve the crossover effect, but could make the difference in performance slightly smaller.

7.3. Tracking Speed and Height

The used setup caused a lag: a delay between the displayed position of the software cursor and the actual position of the user's pointer. The participants needed to get used to the lag in the beginning of the study. I told and demonstrated them that they could go as fast as they needed to be: the digital document and cursor always follows the used device.

In the direct situation, the lag was less bothering the users, compared to the indirect. With indirect, participants depended more strongly on visual feedback to see what they were doing than for the direct case. In the latter situation, participants knew and learned that their own finger or device was directly in contact with the digital document, and assumed that wherever their finger was, the cursor or digital document would follow. More about the accuracy issue is described in section 7.2.

The questionnaires presented that the lower right position at the tabletop display was harder to control than the other positions. That probably occurred because the lower right position could sometimes only be captured by the right motion capture system, while other positions were captured by both motion capture systems.

Interaction without buttons

The devices used to interact with the tabletop display did not have a button. Contact with the table was determined by sensing the height of a device above the table. For example, if the participant's finger was within 3 mm of the table, the system concludes the user is touching the table. A certain range of heights was needed to allow finger thickness differences and angle differences between the finger and the table. It took some time for some participants to get used to this method of making a click. They sometimes needed to move the stylus higher above to table than one normally would do when writing or touching real objects. This lifting made sure that the system knew the stylus is off the table and not interaction with the digital document anymore. Demonstrating the use of the system worked out fine and the participants got used to it. The demonstration took place during block 1 while the demonstrator was still watching and advising them. Generally, participants were getting used to it fast and understood how to use it.

The mouse did not suffer from the height problem because we used the physical button from the mouse itself.

Also occlusion could influence visibility a bit, but there were four locations on the table and the occlusion could only hinder participants a little at the south-east location.

8. Conclusion and Future Work

This thesis investigated factors that influence document passing speed on tabletop displays. Document passing can be done using interaction techniques. These interaction techniques were studied by Mitchell (2003) and Kruger (2005). They both compared two classes of interaction techniques; one instance of the class of an integral technique: *RNT* or *Drag,* and one of the class from a separate technique: *Corner*. The studies found contradictory results: Kruger found that the integral technique was faster, while Mitchell found that the separable technique was faster. This thesis investigated which factors could influence the outcome of both studies in a way that the results conflict.

It could not be solved why both studies found contradicting results. This thesis found that the integral technique was faster in all conditions tested. The factors distance of movement, handle size, precision, device or directness could not influence human performance enough in a way that the separable technique became faster than the integral. This section continues with details on both studies as described in this thesis.

The first research question both studies investigated was:

> *Q1. What is the reason of the crossover effect in human performance as seen in Mitchell's and Kruger's tabletop display studies on document passing?*

The main question about the performance difference between the integral technique and the separable technique could not be solved. The first user study successfully investigated the influence of handle size of an interaction technique, movement distance and precision of a movement task, but could not re-create the crossover effect. The first study focused on the second research question:

> *Q2. What is the influence size of three factors: distance, precision and handle size on document passing?*

The first study found that the influence sizes of these three factors were not as big as predicted and the range of values could not help that *RNT* was the fastest technique in every condition. The *RNT* technique performed estimated 47% faster than the *Corner* technique.

The handle size on both techniques influenced human performance a little, except if small handles with the *Corner* technique was used. Choosing large handles instead of small handles improved an estimated 10% on the *Corner* technique.

The accepted precision at the target location influenced human performance significantly with an estimated 22%.

After the first study was performed, a second study was needed to investigate the influence of possibly other factors influencing tabletop interaction performance. The study 'Device and Directness' compared three devices: stylus, mouse and the user's finger and also compared the indirect versus the direct condition. This study also did not re-create the crossover effect as seen between Kruger's and Mitchell's studies.

The influence of directness is confounded by others factors as visual offset and size of actual movement. The 'Device and Directness' study varied the offset and movement factors together. Directness was shown to have a major influence on performance for tabletop interaction techniques on document passing. Direct interaction performed 36% better on the combined rotation and translation tasks as oppose to indirect situation. In the second study, the *RNT* technique performed estimated 11% faster than the *Corner* technique.

Recommendations

The semi-integral interaction technique, *RNT*, performed faster than the separated technique *Corner*. As Jacob et al. presented (1994), more integral techniques likely perform better on tasks that have a corresponding level of integrality. It is interesting to investigate how techniques with three or more degrees of freedom, such as *Two Point* or other techniques using multipoint contact (Hancock et al., 2006), will perform on combined document rotation and translation tasks.

The 2+1 degree of freedom interaction technique, *RNT*, outperformed the separate technique in the conditions compared in this thesis. As stated in the previous recommendation, an integral technique, using 3 DOF or more, likely performs even better on tasks that need 3 DOF, such as combined document rotation and translation tasks. The third degree of freedom can for example be added by using an extra contact point, as *Two Point* shows. But in some situations, the user might only use one contact point and as a consequence, only separate or a semi-integral techniques can be used. A combination of techniques might provide faster performance when the amount of contact points can not be assured. During the period of interaction, the techniques could be switched, depending on the actual amount of contact points. The translation-only area at the center, on *RNT,* could also be used with techniques similar to *Two Point*. It is not clear if switching techniques confuses the user and affect performance negatively; the last future work section describes this issue in general.

As written in section 7.2, the accuracy of the LEDs and capture system might add an imprecision. The accuracy of the motion capture system could be improved by using high precision LEDs. These LEDs are smaller and emit a smaller beam of light. Using these LEDs likely helps the detection of smaller movements and will achieve a higher precision. Smaller corners and high precision movements would probably benefit from these LEDs. Indirect interaction likely also benefits from a higher precision, since indirect interaction benefits more from small and precise movements.

As written in section 7.3, there was a small lag noticeable between the physical position of the participant's finger at the table, and the actual displayed position of the cursor. It was not measured how long the lag was, but no matter the speed of the participant's hand, the document always followed the cursor, as long as the participant was interacting with the display. It would have been better if the participants would not have experienced any delay between their hand position and the cursor placement. During the test setup, also the LCD display was used and the lag was not noticeable. Likely, the delay was not caused by the motion capture system or the calculations of the software used, because it was not noticeable using the LCD display. During both studies, a ceiling mounted projector was used and likely caused a lag, see figure 13 for the setup. The latency could be caused by the image rotation function of the projector. The rotation function is likely executed in a digital way, which needs time to process. Therefore, a projector setup should be used with a lower latency, by using a different projector or putting the projector in a different setup so that no digital image processing needs to be used.

Future Work

As written before, it is not clear what caused the crossover effect in the prior studies. The study 'Factors Influencing Tabletop Speed' showed that if precision increases, the relative performance of the *RNT* technique decreases, see section 4.6. It might be interesting to investigate in high precision interaction situations and verify if a higher level of integrality continues to benefit performance when having tasks with a corresponding level of integrality.

The study 'Device and Directness' compared the direct versus the indirect situation using a small inset area on the tabletop display. It might be interesting to investigate how the size of the indirect workspace influences performance. For example, a touch pad sized area, commonly used on laptops, could be compared to the inset area size of the second study, as described in this thesis. Indirect interaction techniques might benefit from the familiarity of the use of a touch pad, but for example, the size of a touch pad does not allow long movements. Future use of indirect interaction techniques, using similar inset spaces on tabletop displays, might benefit from an optimal sized workspace.

During both studies, it was not clear how much the performance was due to the level of the accuracy of the used input techniques. Section 7.2 explains and estimates the influence of the accuracy of both studies, but it is still not clear if accuracy influences a separate technique differently than an integral technique, or if it influences at all. Work could be done investigating the effects of input accuracy, comparing a coarse versus a fine input grid.

Some situations might benefit from live switching interaction techniques, depending on the amount of contact points available, as the second recommendation explains in detail. When tabletop interaction designers have to deal with these situations, it might be useful to know how users adapt to on-the-fly switching of interaction techniques and how performance is influenced by changing techniques.

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Appendix

A. Detailed Results - User Study 1

Trial results from the first study, block 3 & 4, (N=8), after data cleaning.

Some values are formated bold because they reflect the condition used in previous study. These bold values correspond with the studies as named in the last column.

	#	Handle	Distance	Precision	Total	Acq	Dock	Sdev T	Sdev. A	Sdev D	Corresponding study
RNT	1	20	571	26	3.10	0.85	2.26	1.47	0.28	1.44	
	2	20	571	46	**2.22**	0.84	1.38	0.74	0.32	0.56	Kruger (task 2)
	3	20	202	26	**2.43**	0.85	1.59	1.04	0.24	0.97	Kruger (task 1)
	4	20	202	46	1.62	0.83	0.79	0.45	0.24	0.36	
	5	35	571	26	2.80	0.79	2.02	1.21	0.23	1.18	
	6	35	571	46	**2.16**	0.79	1.37	0.51	0.24	0.52	Kirkpatrick; Study 2
	7	35	202	26	2.29	0.80	1.49	1.10	0.24	1.11	
	8	35	202	46	**1.80**	0.84	0.95	0.60	0.18	0.59	Study 2: Directness
	9	50	571	26	3.00	0.85	2.15	1.04	0.26	0.99	
	10	50	571	46	2.18	0.87	1.31	0.65	0.46	0.53	
	11	50	202	26	**2.14**	0.82	1.31	0.85	0.24	0.87	Kirkpatrick
	12	50	202	46	1.68	0.82	0.86	0.42	0.27	0.43	
Corner	1	20	571	26	4.24	0.71	3.53	1.46	0.17	1.46	
	2	20	571	46	**3.81**	0.75	3.06	1.25	0.19	1.24	Kruger (task 2)
	3	20	202	26	**3.81**	0.73	3.08	1.42	0.32	1.41	Kruger (task 1)
	4	20	202	46	3.30	0.71	2.59	1.24	0.24	1.24	
	5	35	571	26	3.74	0.71	3.02	1.16	0.29	1.06	
	6	35	571	46	**3.14**	0.69	2.45	0.89	0.24	0.89	Study 2: Directness
	7	35	202	26	3.07	0.75	2.32	0.65	0.25	0.59	
	8	35	202	46	**2.67**	0.72	1.95	0.96	0.21	0.90	Study 2: Directness
	9	50	571	26	3.81	0.72	3.08	1.29	0.31	1.21	
	10	50	571	46	2.95	0.71	2.24	0.55	0.34	0.46	
	11	50	202	26	**3.01**	0.75	2.26	0.97	0.24	0.99	Kirkpatrick
	12	50	202	46	2.52	0.77	1.75	0.46	0.26	0.33	

	Ratio	
Corner / RNT	1.41	using same conditions as Kirkpatrick's study
Corner / RNT	1.72	using same conditions as Kruger's study (task 2)
Corner / RNT	1.57	using same conditions as Kruger's study (task 1)
Corner / RNT	1.48	using same conditions as Study 2 in this thesis

Table 15: detailed conditions and results of the first user study in seconds

Explanation of columns used

RNT/ Corner	The first user study. The interaction techniques *RNT* and *Corner*.
Condition	A numbered list of different conditions. The numbers are connected to a handle, precision and distance combination.
Handle	The handle size in millimeters. Valid as the width of every squared corner in *Corner* and for *RNT* as the diameter of the circle.
Precision	The size of the target corners (valid for every interaction technique). The sizes of the corners influence the precision directly. These sizes allow a certain rotation variation to be valid. A 26 millimeter target corner width corresponds with an 8° rotation, and 46 millimeter corresponds with a 15° rotation. These rotations are measured with a document perfectly aligned in the middle of the document.

Distance	The center-to-center distance in millimeters between the start location to the target location.
Total	The total time in seconds between the start of a typical trial and when the document is correctly aligned. The total time is build up from an acquisition time and a docking time.
Acq	The acquisition time in seconds of a document in a trial. This is measured from the start of a trial, which is when the document and target are displayed, until the document receives its first click from the mouse or finger. The remainder of a trial is not measured in the acquisition time, nevertheless the document is clicked again.
Dock	The docking time in seconds of a document in a trial. This is measured from the start of an interaction with the document, which is when the document is clicked with the mouse or finger, until the document is correctly aligned. The time added in a trial before the correctly aligned document gets accepted (700 ms) is not measured.
SdevT	Standard deviation of the total time in seconds.
SdevA	Standard deviation of the acquisition time in seconds.
SdevD	Standard deviation of the docking time in seconds.

B. Detailed Results - User Study 2

Trial results study 'Device and Directness' from block 3 & 4, (N=18), after data cleaning.

	#	Device	Distance	Directness	Total	Acq	Dock	SdevT	Sdev.A	SdevD	Corresponding study
RNT	1	Stylus	202	Direct	2.59	1.07	1.49	1.29	0.50	1.02	
	2	Stylus	202	Inset	3.51	0.94	2.56	1.61	0.42	1.59	
	3	Stylus	571	Direct	**3.06**	1.03	2.03	1.23	0.47	1.00	Kruger, task 2 (2003)
	4	Stylus	571	Inset	4.33	1.07	3.25	1.78	0.55	1.70	
	5	Finger	202	Direct	**2.65**	1.06	1.57	1.48	0.56	1.31	Study 1
	6	Finger	202	Inset	3.60	1.11	2.49	1.65	0.46	1.57	
	7	Finger	571	Direct	**2.86**	1.04	1.81	1.42	0.60	1.03	Study 1
	8	Finger	571	Inset	4.14	1.13	2.98	1.59	0.63	1.55	
	9	Mouse	202	Direct	2.96	1.24	1.70	1.48	0.70	1.28	
	10	Mouse	202	Inset	**3.56**	1.20	2.36	1.60	0.61	1.49	Kirkpatrick et al. (2006)
	11	Mouse	571	Direct	3.45	1.14	2.26	1.55	0.67	1.37	
	12	Mouse	571	Inset	3.89	1.20	2.69	1.50	0.61	1.36	
Corner	1	Stylus	202	Direct	2.55	0.76	1.78	0.60	0.17	0.57	
	2	Stylus	202	Inset	4.14	0.88	3.24	1.48	0.39	1.42	
	3	Stylus	571	Direct	**3.44**	0.83	2.61	1.10	0.31	1.02	Kruger, task 2 (2003)
	4	Stylus	571	Inset	4.80	0.82	3.98	1.62	0.34	1.60	
	5	Finger	202	Direct	**2.71**	0.72	1.99	1.08	0.26	1.07	Study 1
	6	Finger	202	Inset	4.06	0.98	3.08	1.56	0.54	1.51	
	7	Finger	571	Direct	**3.08**	0.73	2.34	0.90	0.28	0.81	Study 1
	8	Finger	571	Inset	4.45	0.88	3.55	1.28	0.34	1.22	
	9	Mouse	202	Direct	2.92	0.85	2.08	0.78	0.39	0.69	
	10	Mouse	202	Inset	**3.56**	1.01	2.54	1.03	0.39	0.97	Kirkpatrick et al. (2006)
	11	Mouse	571	Direct	3.38	0.85	2.53	0.88	0.23	0.82	
	12	Mouse	571	Inset	4.27	0.94	3.30	1.27	0.49	1.18	

	Ratio	
Corner / RNT	1.00	using same conditions as Kirkpatrick's study
Corner / RNT	1.12	using same conditions as Kruger's study (task 2)
Corner / RNT	1.02	using same conditions as Study 1, short distance
Corner / RNT	1.08	using same conditions as Study 1, long distance

Table 16: detailed conditions and results of the second study in seconds, distance in mm

Explanation of columns used

Device	The used device or method to interact with the system. Study 2 used a stylus, mouse and users own finger.
Directness	Used level of directness: direct or the inset interaction.

Some values are bold because they reflect the condition used in previous study. Table 16 has more columns, but they are equal to the first user study and are already explained below table 15.

Table 17 presents average movement times and standard deviations by device, directness and interaction technique.

Device	Offset	Av. trial time RNT	Std. Deviation RNT	Av. trial time Corner	Std. Deviation Corner
Stylus	Direct	2.83	1.28	2.99	0.99
	Indirect	3.91	1.74	4.46	1.58
Finger	Direct	2.76	1.45	2.89	1.01
	Indirect	3.87	1.64	4.25	1.44
Mouse	Direct	3.20	1.53	3.15	0.86
	Indirect	3.72	1.56	3.92	1.21

Table 17: Average movement times (s) by device and directness

Condition	Average trial time	SD	Acq. Time	Average trial time	SD	Acq. Time
Direct (RNT & Corner)	2.97	1.22	0.94			
Indirect (RNT & Corner)	4.02	1.55	1.01			
Stylus Direct	2.91	1.14	0.92			
Stylus Indirect	4.18	1.68	0.93			
Finger Direct	2.83	1.25	0.89			
Finger Indirect	4.06	1.55	1.02			
Mouse Direct	3.18	1.24	1.02			
Mouse Indirect	3.82	1.39	1.08			
Condition per Interaction Technique	**RNT**			**Corner**		
Overall time	3.38	1.61	1.10	3.59	1.35	0.85
Direct	2.93	1.43	1.10	3.01	0.96	0.79
Indirect	3.83	1.65	1.11	4.20	1.43	0.92
Stylus	3.36	1.61	1.03	3.68	1.49	0.82
Finger	3.31	1.64	1.08	3.57	1.41	0.83
Mouse	3.46	1.56	1.20	3.53	1.11	0.91

Table 18: Average movement times, SDs and acquisition time (all in seconds)

C. Completion Times by Participant

The completion times, in milliseconds, presented in a box-and-whisker diagram. The (red) lines inside the boxes are the median values; the (blue) boxes depict the range between the lower and upper quantile. Note that study 2 'Device and Directness' has a mixed-effect design and therefore participants did the direct or the indirect situation. This is marked by the 'D' or 'I' character on top of the graph. Only the last two blocks out of four were used, because the first two were used to practice.

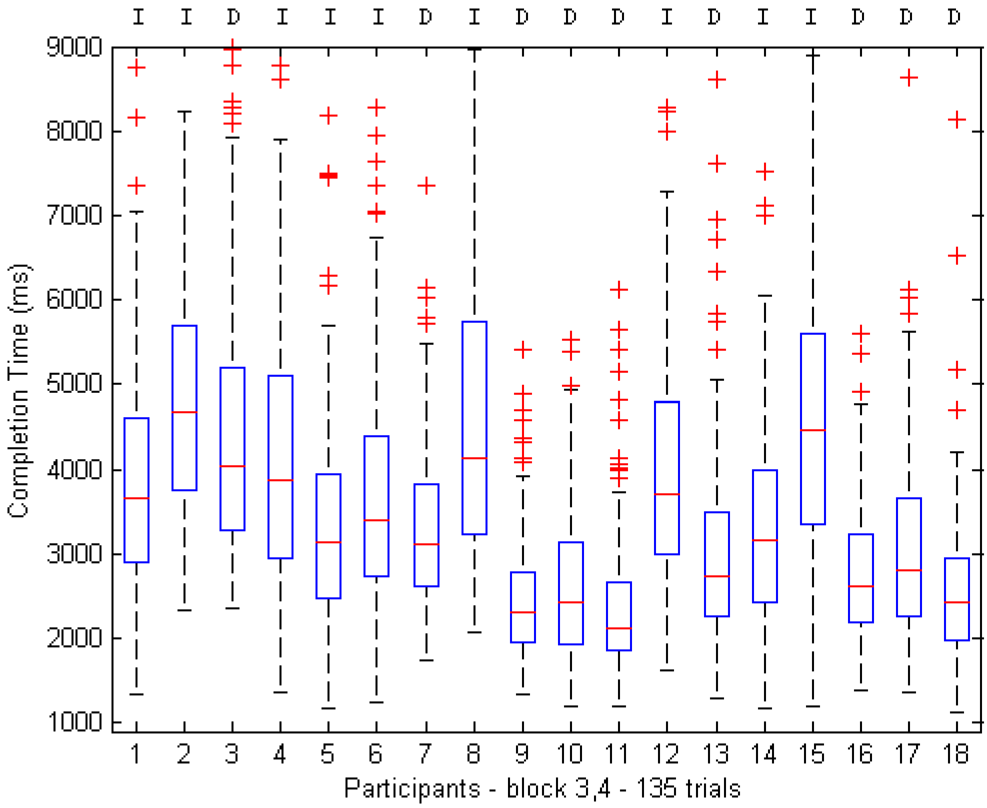

Figure 23: Completion times by participant for the second study. The character at the first line: "I" stands for Inset, "D" for Direct. Data from blocks 3 & 4 are used.

D. Performance per Block

Figures 24 and 25 present the average completion time per block on the *Corner* and *RNT* technique for study Device and Directness.

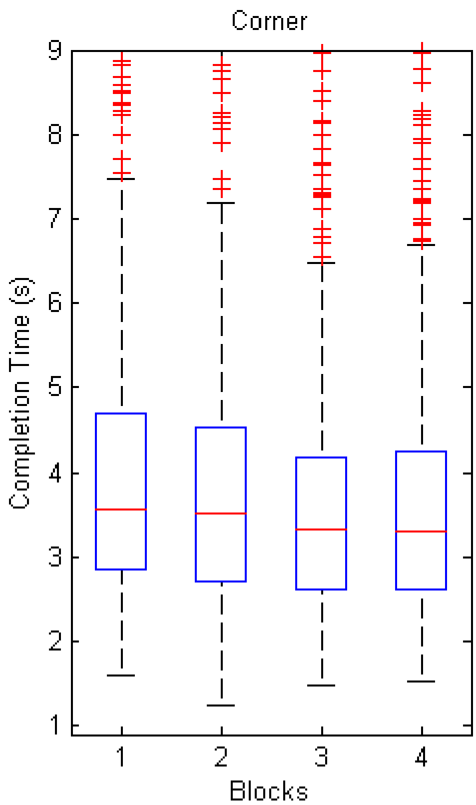

Figure 24: Performance per block on Corner

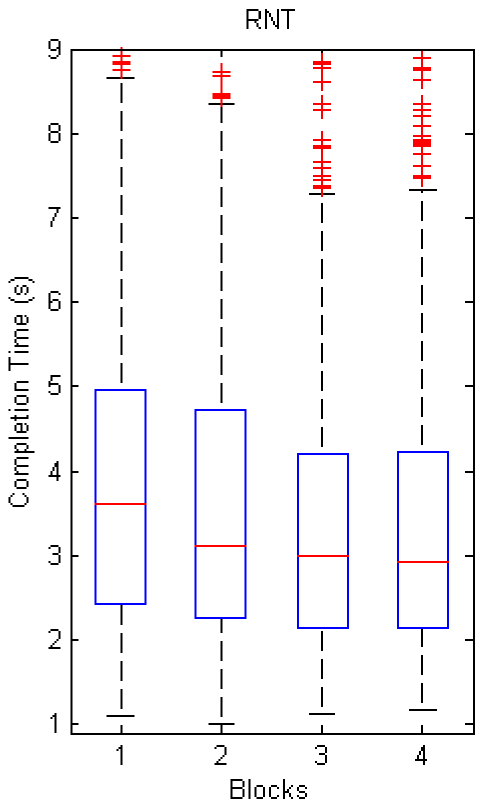

Figure 25: Performance per block on RNT

E. First Document Contact Point Graphs

The following two graphs present the first contact point of the digital document in screen coordinates. These data were extracted from the available path data files of the direct trials.

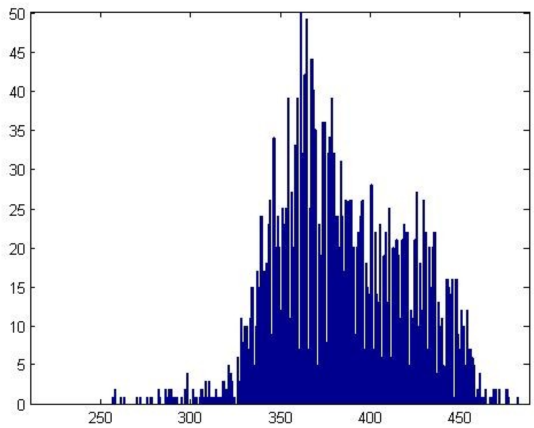

Figure 26: Initial contact position: horizontally display X coordinates in pixels, vertically counts

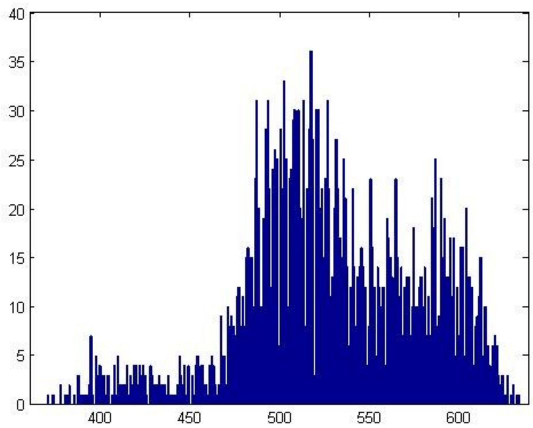

Figure 27: Initial contact position: horizontally display Y coordinates in pixels, vertically counts

F. Participant Order in User Studies

Table 19 presents the used counterbalanced order for the first study, for every participant.

Participant number	Interaction Technique Order
1	RNT Corner
2	RNT Corner
3	Corner RNT
4	Corner RNT
5	Corner RNT
6	RNT Corner
7	RNT Corner
8	Corner RNT

Table 19: First user study: order of interaction technique was counterbalanced, and the participants were randomly assigned to an ordering.

Table 20 presents the used order in study Device and Directness for every participant.

Partici-pant	Block 1	Block 2	Block 3	Block 4	Block 5	Block 6	Direct-ness
1	Stylus - Corner	Stylus - RNT	Mouse - Corner	Mouse - RNT	Finger - RNT	Finger - Corner	Inset
2	Mouse - Corner	Mouse - RNT	Finger - RNT	Finger - Corner	Stylus - Corner	Stylus - RNT	Inset
3	Finger - RNT	Finger - Corner	Stylus - Corner	Stylus - RNT	Mouse - RNT	Mouse - Corner	Direct
4	Stylus - Corner	Stylus - RNT	Mouse - Corner	Mouse - RNT	Finger - RNT	Finger - Corner	Inset
5	Finger - RNT	Finger - Corner	Stylus - Corner	Stylus - RNT	Mouse - Corner	Mouse - RNT	Inset
6	Mouse - RNT	Mouse - Corner	Finger - Corner	Finger - RNT	Stylus - RNT	Stylus - Corner	Inset
7	Finger - RNT	Finger - Corner	Stylus - Corner	Stylus - RNT	Mouse - RNT	Mouse - Corner	Direct
8	Stylus - Corner	Stylus - RNT	Mouse - Corner	Mouse - RNT	Finger - RNT	Finger - Corner	Inset
9	Finger - RNT	Finger - Corner	Stylus - RNT	Stylus - Corner	Mouse - RNT	Mouse - Corner	Direct
10	Mouse - Corner	Mouse - RNT	Finger - Corner	Finger - RNT	Stylus - RNT	Stylus - Corner	Direct
11	Stylus - Corner	Stylus - RNT	Mouse - Corner	Mouse - RNT	Finger - RNT	Finger - Corner	Direct
12	Mouse - RNT	Mouse - Corner	Finger - Corner	Finger - RNT	Stylus - Corner	Stylus - RNT	Inset
13	Mouse - Corner	Mouse - RNT	Finger - RNT	Finger - Corner	Stylus - Corner	Stylus - RNT	Direct
14	Finger - RNT	Finger - Corner	Stylus - Corner	Stylus - RNT	Mouse - RNT	Mouse - Corner	Inset
15	Finger - RNT	Finger - Corner	Stylus - RNT	Stylus - Corner	Mouse - RNT	Mouse - Corner	Inset
16	Stylus - RNT	Stylus - Corner	Mouse - Corner	Mouse - RNT	Finger - Corner	Finger - RNT	Direct
17	Mouse - RNT	Mouse - Corner	Finger - Corner	Finger - RNT	Stylus - RNT	Stylus - Corner	Direct
18	Stylus - RNT	Stylus - Corner	Mouse - RNT	Mouse - Corner	Finger - Corner	Finger - RNT	Direct

Table 20: Second user study: order of interaction technique and device. The order of interaction technique, distance, target orientation, directness and device were counterbalanced and the participants were randomly assigned to an ordering.

G. Detailed Questionnaire Response

G.1. Study 1: 'Factors influencing tabletop speed'

Detailed general questionnaire responses. All the comments of the 8 participants are included! Nothing is summarized or removed.

Corner
- Advantages
Movements could be rougher, since the adjustment would be made in the later rotation.
Rot&Trans are separated.

Quite straightforward.
Not mentally demanding.
Easier to align, less translation problems but more rotation problems.
Clear movement, don't need to consider the sequence of movements.
Easier to manipulate a document.

- Disadvantages
More finger lifting and more planning to break up trial into 2 steps.
Click twice. Rotating first needs judging if rectangle is parallel to target location.
Small corners are hard to rotate.
Two distinct movements but this effort yields more precise alignment (which is a good thing).
Boring.
Two clicks.
Have to use two steps or more. Have to predict the place of the rectangle to be moved before rotate it to match the right place.
Need 2 clicks.

RNT
- Advantages
Could finish in one move; More instinctive: think less.
One click is enough.
One click.
Less physical demand than Corner: since 1 movement is enough.
Fun.
Single click.
Easier to rotate and adjust the direction. Faster if practiced more.
Needs 1 click.

- Disadvantages
To do the task in one move, the rectangle should be moved in a more precise manner
Need to judge which position to drag, since good positions are needed for rot&trans.
Not as straightforward as Corner.
More mental demand than Corner: one movement, more thinking about the finger placement.
Harder to align.
Harder to control to move the rectangle precisely to the target, if I use just one movement.
Problem dealing with rotation and translation at the same time.

General comments
Difficult to rotate when corners were small, with Corner.
Have to bend my neck and back, which is physically uncomfortable.
Maybe after some practice RNT would be preferred.
More physical effort than mental effort was required for completing the tasks. I think after more practice RNT would be preferred.
Would be easier to pan and rotate with whole hand as opposed to one. (pointing finger felt a bit numb after a while)
Height of the table need tuning, was uncomfortable for me.
In Corner, small corners are too small. But if four circles in target are small, both IT's are less successful than bigger circles in the target.

G.2. Study 2: 'Device and Directness'

Detailed general questionnaire response for study 2: 'Device and Directness', summarized.

Inset Condition Participants

*** Stylus**
- Disadvantages
Its movement is different from normal writing. For RNT: hard to keep track of the rotating rectangle. Not fluid, choppy motion. Didn't like picking up the pen constantly. Should keep pen upright, that's not very natural. Hard to control.

- Advantages
Lighter, easier to move than mouse. Looks like normal tools we are using, less intimidating. Easy to use, lot like writing. Most comfortable to use. Interesting to use.

*** Mouse**
- Disadvantages
Wrist pain. Need to carry an extra device in real-life application. Bulky, poor maneuverability. Feels less comfortable for rotating, due to the mouse size.

- Advantages
Everyday using device -> comfortable, no adaptation time. Familiar with. Easy to hold, wrist stays on the table.

*** Finger**
- Disadvantages
Clicking accuracy. Not as sensitive as mouse. Load at arm/wrist. To sensitive

- Advantages
Very natural, good mapping of wrist -> mouse movement.
Use your own body, no need to carry other device. Better then other devices. More control. Easier and faster to pick up. Interesting to use. Feels natural. VR-effect.

*** Corner&RNT**
- Disadvantages
Corner always took several clicks and sometimes quite a bit of adjustment. Need to get used to RNT. RNT was to sensitive. RNT was tedious.

- Advantages
RNT seemed more difficult at the beginning, but would improve more in time / skill. Corner follows every day use of drag and drawing. There is more of a confirmation when using corner. Once used to it, RNT seems to be easier. Corner can be accomplished any time with the same amount of effort.

*** General**
A tilted table might be easier to use if working alone. Wrist felt tired after. I was more comfortable using finger here than using the general touchpad; also the inset was larger then touchpad; much more happy using it. Liked corner best with stylus; liked RNT best with finger (2 participants). Didn't like the lower right corner, hard to pick up paper (device problems).

Direct Situation Participants

*** Stylus**
- Disadvantages
Sometimes the paper is triggered even though the stylus wasn't touching the table. It's easy to be treated as one movement if the stylus is not lifted high enough. Awful sound when moving across the table. Feels like moving paper around with a pencil; feels as though it would be inaccurate, though it wasn't.

- Advantages
Easy to grab. Can touch area where I want accurately. Can be put away out table easily. Very intuitive. Easy to use. Pleasant to use, more then finger and mouse. Easy to share with other people.

*** Mouse**
- Disadvantages
Cursor of the mouse was to far away from clicking point of the mouse. Cursor moved slower than the mouse, slowing the task down. Have to bend over the table to operate. Get a tired palm after working for a long time. Gets annoying. Slow. Clunky (bending over table).

- Advantages
Easy to grab by hand. I'm used to or familiar to this device (6 participants said the same).

*** Finger**
- Disadvantages
Objects that are away harder to touch. Easy to get tired when working long time. So intuitive that I thought I could use my thumb to move paper as well. Finger gets hot. Sweaty. Takes time to put on.

- Advantage
Touch point is where cursor is. Easy and fast to use. As if I was moving actual paper on a table. Accurate. Comfortable to operate. Easy to move freely. Excellent control & nice feeling.

*** Corner & RNT**
- Disadvantages
RNT gets better after training. RNT is better because does rotating and translating together. RNT has got more physical demand. Corner needs more physical movement. RNT is harder to master. RNT gets better after you are getting skilled. Corner sometimes misjudged angles.

- Advantages

Corner is easy to control. RNT is faster. Corner is straightforward; less mental demand. After getting used to RNT, it is fairly easy with using the stylus. Corner is easy to start with, but after a while gets less convenient and a bit rigid.

*** General**
Ideal if all the three devices are available at the same time. Cool project. When the task is complete it should disable the mouse/stylus/finger detection a second. Would be interesting to simulate weight (momentum) for the paper.

H. Form: User Study information to participants

The complete form, as used in the second user study, is written below.

User Study Information for Participants – July 2006

Name of Experiment Moving and rotating objects on tabletop computer display
Investigator Name Jacob Koster, Ted Kirkpatrick
Investigator department School of Computing Science

Risks
There are no reasonably foreseeable risks to participation. You will be using a part of a glove and a tabletop display. You will be given breaks every few minutes. If you decide to participate, you are free to discontinue participation at any time during the study if you wish to do so.

Benefits
You will be contributing to the advancement of our understanding of how people can effectively use a new high-tech user interface, a tabletop display.

Confidentiality
The summary results of this study will be made publicly available in a scientific paper or other public form for other researchers. However, your identity will not be recorded in this study. All the data will be filed under a numeric code assigned for the study, and there will be no way that individual participants will be identifiable from the data.

What The Participant is Required to Do
This study examines three different techniques for moving and rotating a digital document on a tabletop display. While you do the tasks, the computer will record how the digital document is moved around, so afterwards we can analyze this data to understand the different techniques. There is no 'wrong way' to do things.

Task
The same basic task is repeated throughout the experiment. You will line up a rectangle with a target.

- The rectangle is considered lined up when the corners lie inside the circles. At this point, the circles will turn yellow.
- When it is been lined up for 0.7 seconds, the trial will automatically end and a box will pop up with a button to start the next trial.
- Any location of the rectangle that makes the target corners turn yellow is fine. You do not have to line up the rectangle any more accurately than that.

Overall flow of the session
For each interaction technique, you'll:

Practice

- We show you how the technique works, then you do 8 practice trials.
- Then a box pops up letting you go to the experiment

Blocks

The trials are grouped into a couple of different “blocks”, with a short break between each block.

- Each trial will start by clicking a “Start Next Trial” button.
- If you need to rest or you have a question, please do it only after you've finished a trial, while the “Start Next Trial” box is displayed. Stopping in the middle of a trial will affect the timing data.
- After finishing a block of trials, the screen will tell you the block is finished and you have a chance to rest. After a brief time the rest will finish and you can start the next block.

Questionnaires
At the end of using each technique (that is when 4 blocks are finished) you will fill out a digital questionnaire:

- Rate the 'workload' of using the technique, how difficult it was, in 6 categories.

Final questionnaire
After completing all the trials, you will fill out a final paper questionnaire, a preference ranking and your opinion about the techniques used.

That's it! Thanks for your help.

I. Form: Background information participants

Code #: _______ To preserve your confidentiality, this form only refers to you by a code number, not your name. No one will be able to connect these answers to you.

Background information

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

Age: _______

Gender: Female _____ Male _____

Approximately how many *hours per week* do you use a computer (please check the closest answer)?

Less than a half hour a week	Less than 2 hours a week	Less than 7 hours a week	Less than 14 hours a week	14 or more hours a week

Experience
How much have you used the following input techniques? Please check the best answer.

	Never	Have used a little	Use it, but not regularly	Currently use it every week	Currently use it every day
Mouse					
Rotating objects on a computer by dragging the corner (say, in an					

art program)					
Tabletop (horizontal) display, activated by direct touch					

Which hand do you prefer for **writing**? Right ______ Left _________ Either _______

Which hand do you use the **mouse**? Right ______ Left _________ Either _______

J. Form: Instructions for the experimenter

The experiment should be conducted in the same manner and order. Therefore this form was used in the second study.

Instructions for the experimenter

Introduction

Welcome. Welcome the participant.

Summary sheet. Have them read the summary sheet for the experiment.

Consent form. Have them read the consent form completely, then sign it. Offer them a copy of the consent form to keep for their records. Keep the signed consent form in the consent form file, and keep the file in a secure place.

Background questionnaire. Have them fill this out.

Physical

Finger from Glove. Try to fit one of the two fingers, depending on the finger size of the participant. The finger glove should fit tight to the user's hand. Ask if it is okay to tape the wire to the participant's elbow and shoulder (2 points). If possible, the LED wire box might fit into the user's pants.

Observers. Remind the participant that there are no video cameras or people in the other room observing the session. You will be in the room watching, but no one else will. (If another experimenter, such as Ted, wishes to be in the room as well, that is fine.)

Practice Trials

Demonstration of first technique. Use your 8 demonstration trials to show the user

- That the target lights up automatically when the document is correctly positioned. Show that the colours have to be correctly aligned.
- That they should try to be as fast as possible, and just accurate enough to get the target lit.
- Point out the different regions of the object (slide vs. rotate in Corner, slide-only vs. slide+rotate in RNT).
- The general strategy for the first technique.

Strategy for Corner

You can either do a slide first, followed by a rotate, or the other way around.

Strategy for RNT

Try to do it in a single move, even you can do it faster with several different moves. However, if you have the document right over the target and a small slide will get you in the right place, feel free to click in the slide-only region.

Plan your move before starting it. Figure out the direction you are going to enter the target and where you are going to drag from. Your fastest path may not be the most direct.

This technique permits you to rotate more than Drag, with less sliding.

Eight practice trials

Comments. Watch the user carefully as they do these trials and give feedback. Suggest alternative strategies. Commiserate when a move goes badly, and celebrate when one goes particularly well. If the user is having a hard time using the technique effectively, in the midst of a difficult trial suggest that they back up to start, show them where to click, and a better path. You can even complete the trial yourself, to demonstrate a better way to do it.

Tell them to take as long as they want on these trials.

Tell them they don't need to lift up their finger to complete a trial! This helps to keep the digital paper steady on its place. Lifting up the finger or device sometimes shifts the document.

Check-in for physical comfort

Ask them if they are comfortable or if they would like to adjust the display position, chair position, mouse position, or anything else.

Breaks

Encourage them to take a break when the computer advices them to take one. Standing 4 blocks can be quite long, they can use the chair to sit on during the break, but not during the trials.

Blocks 1

Comments. Feel free to give comments during these blocks as well. You may also intervene, as in the practice trials. Don't worry that the trial time will be long. Point out to the participant that they are welcome to continue exploring and trying new strategies. You can still, on occasion, actually complete the trial.

Breaks. Recommend that they take breaks between blocks, rather than just skipping the breaks and going on.

Blocks 2, 3 and 4

No comments. Do not provide any feedback or comments while the user works in these blocks. Tell them that they are on their own. Ask them to do these trials as quickly as they possibly can.

General instructions for experimenter

Do not suggest that any technique is faster than any other. We don't want to give them prior expectations.

Mention that you did not develop any of the techniques. This experiment is to learn more about techniques developed by other people.

After the trials

After every IT and every device change, let them fill in the TLX questionnaire.

After all the ITs are finished, and the last TLX questionnaire is done, the Open ended post questionnaire must be filled in. Also the preference ranking should be filled in. When the participant is ready, verify if the text filled in is readable and if the participant didn't forget anything. Let the participant fill in the receipt and give him the money.

K. Form: TLX Questionnaire for participants

The NASA TLX questionnaire as used in the both the studies. The preference ranking, at the end, is adapted for the second study.

Code #: ______ To preserve your confidentiality, this form only refers to you by a code number, not your name. No one will be able to connect these answers to you.

Importance of Different Workload Categories

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

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

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

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

Preference Ranking 1

Rank the **techniques** according to your preference for the stated condition. Assign a 1-2 ranking according to your best estimate (1 = most preferred, 2 = least-preferred).

Rank	**Technique**
	Corner (with the squares at the corners)
	RNT (with the circle in the middle)

Preference Ranking 2

Rank the **devices** according to your preference for the stated condition. Assign a 1-2-3 ranking according to your best estimate (1 = most preferred, 2 = middle preferred, 3 = least-preferred).

Rank	**Device**
	Stylus
	Finger
	Mouse

L. Form: Open ended Questionnaire for participants

The following form was used at the end of the user study by every participant. This specific form was adapted and used for the second study.

Code #: __ To preserve your confidentiality, this form only refers to you by a code number, not your name. No one will be able to connect these answers to you.

General Questionnaire

Briefly describe the most significant advantages and disadvantages:

a) Stylus

Disadvantages:

____

____

Advantages:

____

____

b) Mouse

Disadvantages:

____

____

Advantages:

c) Finger

Disadvantages:

Advantages:

d) Corner and RNT

Disadvantages:

Advantages:

e) General comments

Thanks!

M. Form: Ethics Approval

The following forms were needed, according to the Simon Fraser University policy (published at http://www.sfu.ca/policies/research/r20-01.htm), to execute a user study. They are a reply from the Research Ethics Board, at our user study approval request.

FOR CONTACT IN REFERENCE TO THIS REVIEW

Application Number 37579

Page 1

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Director, Office of Research Ethics

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Reference Ethics Policy 20.02: http://www.sfu.ca/policies/research/r20-01revised.htm

Notification of Application Status

Investigator Name Last
Koster

Investigator Name First
Jacob

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Investigator or Supervisor
Kirkpatrick Arthur

Co-Investigatorsors or Collaborators
Arthur E. Kirkpatrick

Investigator Department
Computing Science

APPROVED
By Hal Weinberg at 3:02 pm, 6/6/06

Investigator Position
Other (Research Assistant)

Date Created	Date Modified	Code
5/29/2006	6/6/2006	37579

Experiment Title
Comparing tabletop display interaction techniques

Amendments: Note that all ammendments must reference the Application Numer shown above.

Risk
Minimal

DORE Approval Date
June 6, 2006

Approval Status
Approved

Approval Start Date
6/6/2006

Medical or Relevant Review

Last Amended

Approval End Date
6/6/2008

Grant Funding Agency

Grant Funded No

Grant Title for funding agency

Grant Start Date **Grant End Date** **Grant Track Number**

FOR CONTACT IN REFERENCE TO THIS REVIEW

Application Number 37579

Page 2

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B. Ralph, Ethics Officer

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Reference Ethics Policy 20.02: http://www.sfu.ca/policies/research/r20-01revised.htm

Jacob Koster

Your application has been categorized as Minimal Risk and approved by the Director, Office of Research Ethics, on behalf of the Research Ethics Board in accordance with University policy R20.0, www.sfu.ca/policies/research/r20-01.htm. The Board reviews and may amend decisions made independently by the Director, Chair or Deputy Chair, at their regular monthly meetings.

Note: Supervisors of students are co-applicants of the application and are responsible for compliance of the project with terms of REB approval.

Please acknowledge receipt of this Status Notification by email to: dore@sfu.ca.

You should get a letter shortly

Good luck with the project
Hal Weinberg