IMPROVING DIGITAL HANDOFF

IN TABLETOP SHARED WORKSPACES

A Thesis Submitted to the College of

Graduate Studies and Research

In Partial Fulfillment of the Requirements

For the Degree of Master of Science

In the Department of Computer Science

University of Saskatchewan

Saskatoon

By

Jun Liu

Keywords: Handoff, Tabletop Displays, Shared Workspaces

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ABSTRACT

Handoff is a synchronous object transfer technique in face-to-face collaborative work and is one of the low-level actions of collaboration that is smooth and natural in physical settings; however, in digital tabletop workspaces, digital handoff is often awkward and difficult to control. We carried out a series of studies to investigate how digital handoff could be improved in tabletop systems. We first observed people doing several real-world tasks around a standard table and found that handoff is as common in the real-world as deposit (an asynchronous tool transfer technique). The study identified several guidelines to support the design of handoff actions in digital tabletop system. We then examined 2D-handoff techniques; by running a pilot study, we compared the traditional handoff technique with the real-world tangible handoff technique, and found that the traditional digital handoff technique was not well suited for transferring objects on the tabletop. By analyzing the handoff mechanism we spot the bottleneck that affected traditional handoff procedures and designed a novel 2D-handoff technique, force-field technique, which alleviated this bottle-neck to solve this problem. Through a user-study we found that the force-field technique was significantly faster than current digital handoff techniques and as good as real-world 2D-handoff techniques. In addition, force-field handoff was most preferred by a majority of participants. We further designed and implemented a 3D-handoff technique that embodies our observations of how handoff occurs in the real-world setting.

Finally, we evaluated our design in a simulated digital-tabletop task with the goal of assessing the usefulness of various digital transfer techniques including standard deposit, traditional handoff, force-field and 3D-handoff. The results showed that on the digital tabletop system the percentage of using deposit, 2D-handoff and 3D-handoff techniques is similar with the percentage of using these techniques on the real world physical table. 3D-handoff was the most preferred and the most frequently used technique among the handoff techniques; and the force-field technique is preferred than traditional handoff technique.

ACKNOWLEDGMENTS

Thanks for the help given by my supervisors: Dr. Sriram Subramanian, Bernard Champoux and the volunteers who participated in the evaluation. And many thanks to Huijuan Wu, Tad Stach, Miguel Nacenta and Ragu who help me proof read the thesis.

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CHAPTER 1
INTRODUCTION

In the physical world, tables are perhaps the most common sites for shared work with tools and artifacts. Digital tabletop systems [3, 31, 35, 36] are now being built to support collaboration over electronic documents, virtual objects, and digital tools. In these systems, users position themselves around the table and carry out collaborative activities, as much as they work around a physical table. However, digital tabletops are only beginning to approach the flexibility and simplicity that is evident in face-to-face collaboration. In order to enable the smooth and fluid interaction that is visible in physical settings, tabletop workspaces must support the basic low-level actions and interactions that enable people to carry out tasks in a shared fashion.

One of these actions is handoff – the transfer of objects from one person to another. Handoff is frequently used in face-to-face work when one person hands over task artifacts to other persons, pass shared tools back-and-forth, and work collaboratively to move a number of objects from one place to another.

Handoff can be characterized as a multi-person synchronous target acquisition task. The first person brings the object or tool towards the second person, and holds it in position until the second person takes it. The second person then moves the object to a target region somewhere in his working area. The location of handoff is variable for the first person, and may change based on the table or the activities of the receiver.

Handoff is also different from depositing objects or simple reaching. Handoff is a synchronous action but deposit is an asynchronous action in which it is not necessary for the sender's release action and receiver's picking up action to happen at the same time. Handoff needs multiple users to coordinate and collaborate but reaching is a single-person based interaction. In general, handoff needs users to negotiate a complex hand-over of the shared object. In the case of reaching or deposit, the sender simply leaves the object at the transfer point and the receiver reaches to that point to take the object. Handoff and Deposit are useful in different task settings and it is not possible to replace one technique by the other.

Problem

Although handoff is common in real world tabletop, little thought has been given to its design in digital tabletop system. In the real world, handoff happens naturally; because both the sender and receiver can grasp the physical object, see the position of the real object, feel the other person's effort on the object and transfer the object in the 3D space. But in the digital world, there will be no haptic feedback and no physical representation during the object transfers. We do not know whether it is going to slow down the handoff; whether users will feel comfortable to transfer objects with handoff; whether users are going to change their interaction pattern due to lack of physical and 3D representation of the object; and whether there is any way to solve the problem and improve the digital handoff. In short, without the knowledge of how users coordinate the handoff action and what factors affect the transfer, it is difficult to design effective handoff techniques (and consequently transfer techniques) for digital tabletop interactions.

Steps in the Solution

In this thesis, we look more closely at how handoff can be supported in shared tabletop workspaces. Our investigation involves three steps.

The first is an observational study of users performing various highly-integrated tasks involving several tools and artifacts transferring actions on the real table. The purpose of this study was to investigate how often and when users chose handoff and deposit as a transfer technique in real-world tasks. We identify several characteristics that influence the real-world handoff, and use them as guidelines for designing handoff techniques on the digital tabletop system.

The second step was to examine 2D-handoff techniques, where the users handoff actions are restricted to the active work-surface of the table. We first ran a pilot study that compared traditional digital handoff with physical handoff (using a tangible block) techniques. This pilot exemplified problems with the traditional digital handoff method and revealed the bottleneck in handoff negotiation. Based on the findings of the pilot study, an enhanced 2D-handoff technique was designed; we evaluated the techniques through another experiment that compared the new handoff technique with the traditional digital and physical handoff techniques.

The third step was to design an enhanced 3D-handoff technique with which users could access the areas above the active surface of the digital table. This technique typified a basic observation of the real-world handoff action; most handoff actions were not restricted to the work-surface of the tabletop but actually happened above the tabletop surface. We implemented a digital jigsaw puzzle game as the evaluation environment with several transferring techniques available at the same time. Based on our analysis of how and what techniques were used by the participants to transfer objects we identify several design recommendations.

Contributions

The main contributions of this thesis are

- Extend the design space of digital tables to include recommendations for the design of handoff actions.
- Through an observational study explore the benefits of handoff and deposit techniques. We show that in tabletop tasks users transfer tools and artifacts using both handoff and deposit.
- Examine the limitations of digital handoff when user actions are restricted to the active work-surface of the table. Our examination reveals that naïve implementations of handoff on digital tables are significantly slower than real-world handoffs. Based on this, we improve digital handoff by embodying digital objects with force-fields that facilitate faster handoff.
- We further show that handoff (and consequently transfers) in digital tables can approach the fluidity and flexibility of real-world tabletop transfers by allowing users to pass objects in the 3D space above the active work-surface.

Thesis Outline

The rest of the thesis is organized as follows:

In Chapter 2, we present the literature that is related to this research. This includes a review of tabletop systems, interaction techniques, collaboration on the tabletop, and some previous transfer technique research.

In Chapter 3, we describe an observation study and summarize several guidelines for designing handoff techniques on the digital tabletop system.

In Chapter 4, we first investigate current 2D-handoff techniques for digital tabletop systems and identify the bottle-neck of the traditional handoff technique. After that, we introduce a force-field technique, a novel improved 2D-Handoff technique. And we compare various 2D Handoff techniques in a second study and describe the results.

In Chapter 5, we propose a new 3D-handoff technique. In order to compare it with other 3 transfer techniques, we recruit 4 groups of subjects to take a digital jigsaw puzzle game on the digital tabletop system. We analyze how these handoff techniques are used in the digital tabletop task; and compare the differences between the digital world handoff with the real world handoff.

In Chapter 6, we discuss the handoff techniques and their usage on the digital tabletop systems. Then we summarize the conclusion and suggest the possible directions for future improvement.

CHAPTER 2
LITERATURE REVIEW

Tabletop systems

The realization that tables are common in the real-world and offer a natural setting for users to share tools and collaborate has led to a renewed research interest in digital tabletop systems. Digital tabletop systems can be broadly classified based on the type of input they support into 2 categories – touch sensitive tables and mixed-reality tables. In this section, we introduce the important tabletop systems in each category.

Touch sensitive tabletop systems

Touch sensitive tabletop systems support user input through stylus or fingers. Users can to directly touch the active work-surface of the table for the system to sense the position of contact. The active work-surface serves as the visual display that allows users to directly interact with the displayed content through the input device.

Figure 1: Three people collaborate on a PDH tabletop (figure taken from [32]).

The Personal Digital Historian (PDH) [32] is an early example of such a table that supports user input through two Mimio styluses [19] to allow users to share digital photo albums in a casual setting with other users. The active work-surface was created from a top-projection that displays on a standard table. Figure 1 demonstrates a scenario of people using PDH in story telling task. The authors later extended PDH to run on a custom built multi-user, multi-touch tabletop surface called DiamondTouch [3].

Figure 2: Users are working collaboratively on a DiamondTouch system (Figure taken from [3]).

DiamondTouch, in action in Figure 2, is a top-projected digital table [3] that allows multiple touches by a single user and distinguishes from between simultaneous inputs from multiple users. The system uses capacitive coupling between the user and the touch point to uniquely identify inputs from multiple users. DiamondSpin [33] is a toolkit based on the DiamondTouch platform that supports prototyping of tabletop systems for multiple collaborators.

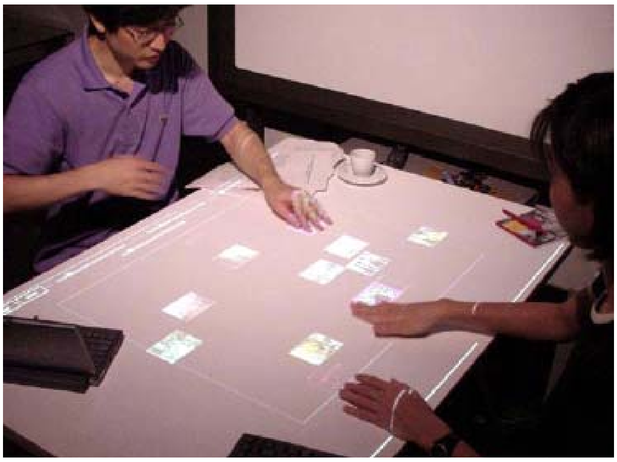


Figure 3: An interactive tabletop surface with the SmartSkin sensor. (Figure taken from [24])

SmartSkin [24] is new sensor configuration developed by SONY that uses a mesh-shaped sensor grid to determine multiple hand positions and gestures, as well as measure the distance between hand and the surface. Figure 3 shows two users using their palms to interact with the SmartSkin tabletop.

Figure 4: Philips Entertaible digital tabletop system (Figure taken from [8])

Recently, Philips introduced a new digital tabletop product, called Entertaible [8]. Entertaible uses proprietary technology to support multi-user, multi-touch interaction while uniquely identifying inputs from multiple users. The benefit of Entertaible is that it supports user interaction on a work-surface that’s created from a compact LCD display preventing undesirable shadows caused by top-projected tables like

DiamondTouch. The system also supports user interaction through specially tagged physical objects. Figure 4 shows that several people are playing electrical board games together on Entertaible.

Mixed-Reality Digital tabletops

Some of the digital tabletop systems allows user to use tangible tools to interact with the virtual objects on the table. These tangible tools allow users to leverage knowledge learnt by interacting with everyday objects to intuitively interact with virtual objects. Most of these systems were developed primarily with the goal of exploring mixed-reality applications which combine virtual and physical objects.

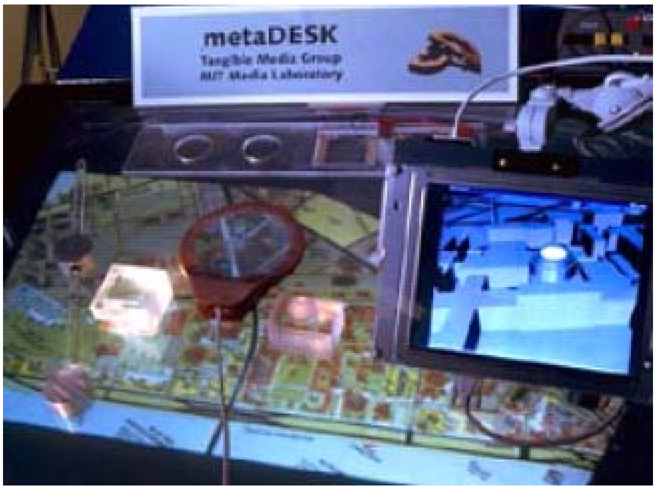


Figure 5: The metaDESK system overview. (Figure taken form [39])

MetaDESK [39] is a geospace exploration system that uses several physical tools for tabletop interaction on a back projected graphical surface. The physical tools are sensed using mechanical, optical and electromagnetic sensors. The system offers a platform to explore physical affordances in tabletop interaction. Figure 5 shows a prototype of the metaDESK system – GeoSpaces. GeoSpace allows the geographic exploration of the MIT Campus using physical tags like MIT dome phicon, the active lens, the passive lens and the rotation constraint instrument.

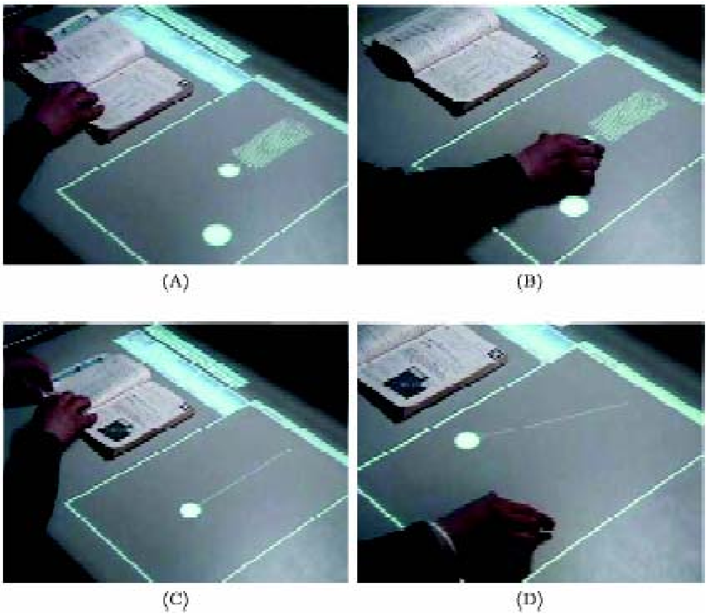


Figure 6: Interactive Textbook in use on Enhanced-Desk system (Figure taken from [13]).

EnhancedDesk is a mixed reality back-projected table that integrates physical paper and digital contents on a desk. EnhancedDesk uses infrared camera to track users' fingers positions, then the system automatically retrieves and displays the digital information that corresponds to users' manipulation for the real physical objects on the table. Figure 6 demonstrates that EnhancedDesk is helping a student to understand the mass-spring experiment.

Figure 7: The Lazy Susan tabletop system from IBM. (Figure taken from [20])

Omojola et al [20] present the digital Lazy Susan system which uses a traditional table with top-projected display and coasters as carriers of digital objects. They attach several sensors to the traditional tables and user can use coasters to represent digital objects. Users can exchange the information by switching the coasters, much like the mediablock presented by Ullmer and Ishii [40]. Figure 7 shows several users sitting around the Lazy Susan and using coasters to exchange information with the other people.

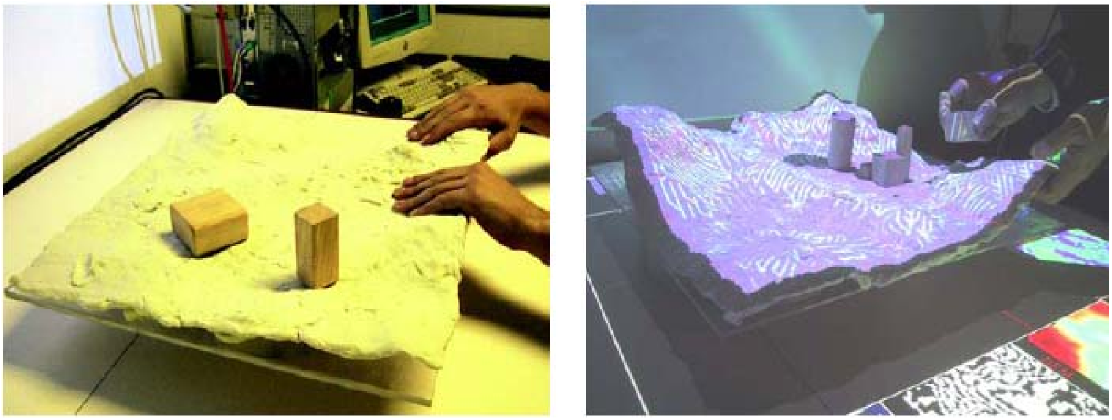


Figure 8: Tangible Illuminating Clay system. (Figure taken from [10])

Tangible Illuminating Clay system [10] uses laser scanner mounted on the ceiling to get the 3D model of the tabletop surface, and top--projected displays to present the graphical image of this 3D model. Users can use “Illuminating Clay” or “SandScape” or any physical objects to adjust the surface of the tabletop during the collaboration. The system allows users to create and edit complex digital 3D models interactively and intuitively by using moldable materials. Figure 8 shows users working on the tabletop surface with their hands and wooden blocks.

Interaction techniques

A wide variety of research has been done into ways that users can interact with data and with each other through digital tables. Users can work together on tabletop displays using single input devices (such as tangible blocks, styluses, mice, or fingers), or using multiple-touch input devices. Since individual actions on a table are also public acts that are available to collaborators, the design of interaction techniques can have a large effect on collaboration.

For example, Inkpen et al. [9] found that a stylus is better than a mouse for user interaction on the tabletop systems. Because the direct-pointing with the stylus provided more effective communication about people's actions, thus it could help the sender and receiver better coordinate their handoff actions.

Figure 9: Two people are using Room Planner (Figure taken from [41]).

Wu and Balakrishnan [41] present multiple-finger and two-handed gestures to allow users to collaborate in a tabletop (Figure 9). These gestures allow users to use everyday gestures like pinching and stretching the corners to resize the window and tossing the virtual object to send it to the far-side of the table. These gestures not only increase the input bandwidth, but also enhance the awareness of other collaborators.

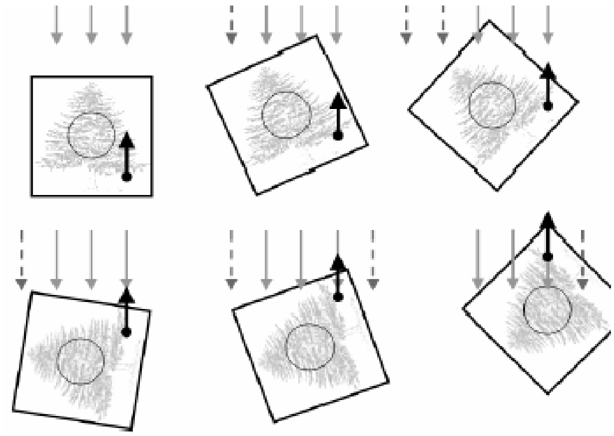


Figure 10: RNT Unbalanced movement (Figure taken from [15]).

Kruger et al. [14, 16] find that object orientation on a tabletop is important for collaboration and handoff actions. Kruger et al. [15] also find that users usually simultaneously rotate and translate artifacts on real-world tabletops. Based on these findings, they present Rn'T a novel technique to simultaneously rotate and translate an object on the tabletop. Figure 10 illustrates Rn'T; it shows the rotation of an object while translating from a control point located in the lower-right corner of the object [15].

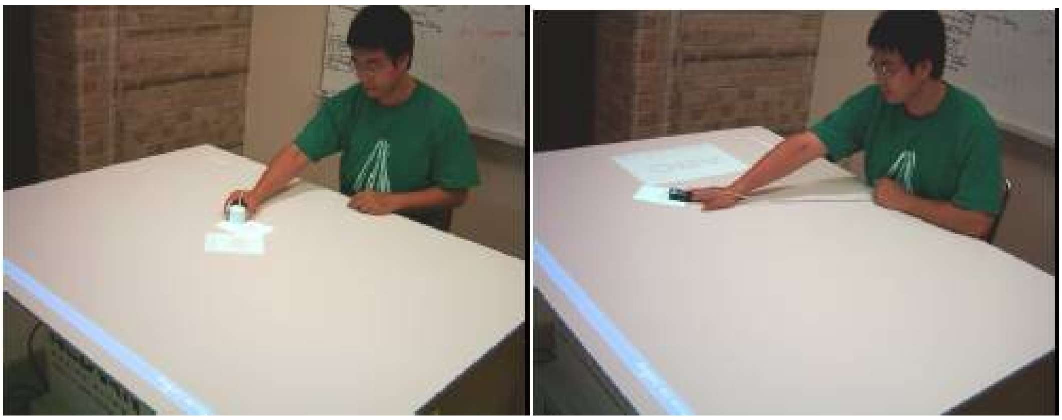


Figure 11: A user is using TNT-block and TNT-hand on the tabletop. (Figure taken from [18])

In a comparative evaluation Liu [18] et al studied the ways that people move and reorient sheets of paper on real-world tabletops. They found that in almost all cases, rotation and translation are carried out simultaneously, and that an open-palm hand position was the most common way to carry out the motion. Based on our observations, we designed a new set of reorientation techniques that more closely parallel real-world motions. The new techniques, Turn and Translation (TNT), use three-degree-of-freedom (3DOF) input to allow simultaneous rotation and translation [18]. Figure 11 shows that a user is using TNT-block and TNT-hand respectively to interact with the objects on the shared workspace.

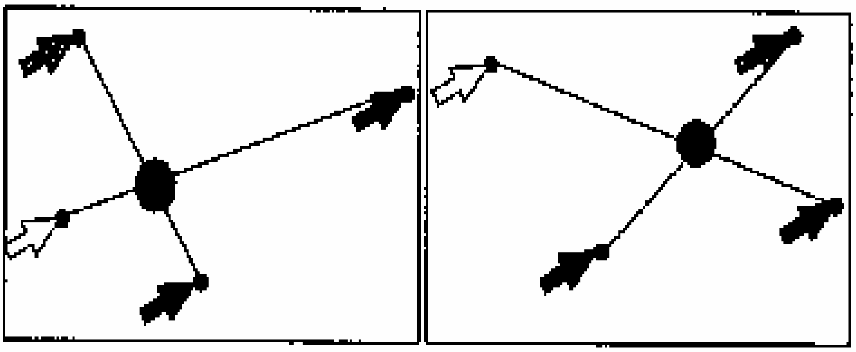


Figure 12: Four users cooperatively controlling the location of a point (figure taken from [17]).

Cooperatively Controlled Object (CCO) [17] allows multiple users to collaboratively interact with one digital artifact synchronously. When several users want to select and move the object at the same time, they need to communicate with each other to solve the confliction. CCO can help them negotiate by applying some constraints to every user. Figure 12 shows that how CCO (a point) is controlled by four conflict users. Every cursor position determines the location of the point and it is also a constraint for the others.

Collaboration

Some characteristics of tabletop collaboration have also been proposed as foundations for the design of interaction techniques. Tang [37] conducted detailed video observations to point out that hand gestures are used to express precise information and the orientation of the tabletop surface serves many functions for user interaction. Stewart et al. [34] demonstrate that people prefer using two hands to do collaborative tasks. And users can use one hand to do their own task while they use the other hand to help and communicate with other people. Hand gestures also help groups members communicate naturally during the collaboration. Bekker et al. [1] analyze people gestures when they engage in designing task, and categorize the type of gestures in face-to-face and remote work, including kinetic gestures, pointing gestures, spatial gestures and other gestures.

Table 2-1. The Mechanics of Collaboration (Table taken from [21])

Category	Mechanic	Typical actions
Communication		
Explicit communication	Spoken messages	Conversational Verbal shadowing
	Written messages	Conversational Persistent
	Gestural messages	Indicating Drawing Demonstrating
	Deictic references	Pointing + conversation
	Manifesting actions	Stylized actions
Information gathering	Basic awareness	Observing who is in the workspace, what are they doing, and where are they working
	Feedthrough	Changes to objects Characteristic signs or sounds
	Consequential communication	Characteristic movement Body position and location Gaze direction
	Overhearing	Presence of talk Specific content
	Visual evidence	Normal actions

Coordination		
Shared access (to tools, objects, space, and time)	Obtain resource	Physically take objects or tools Occupy space
	Reserve resource	Move to closer proximity Notify others of intention
	Protect work	Monitor others' actions in area Notify others of protection
Transfer	Handoff object	Physically give/take object Verbally offer/accept object
	Deposit	Place object and notify

Pinelle et al. [21] propose the mechanics of collaboration as a set of low-level actions and interactions that must be supported if team members are to accomplish a task in a collaborative fashion. And the handoff action is one of these actions (Table 2-1).

Kruger et al. [14, 16] studied the role of spatial orientation on communication and collaboration, through observational studies of collaborative activity on a traditional table. They found that objects orientation is important for users' *comprehension*, *coordination* and *communication*, during the tabletop collaboration. *Comprehension*: On the tabletop, the content is shared by the others. It is often difficult to understand the content of the artifacts. And people rotate items to different angles to help them understand or interact with content. *Coordination*: People tend to coordinate with each other by establishing shared spaces on a table, and communicate ownership of the artifacts in the shared spaces by orienting objects. *Communication*: Orientation also helps collaborators to do some intentional communication between individuals. This includes intentional communication, and independence of orientation. Krish et al. [12] also indicated that sometimes users unintentionally rotate and relocate the object. Because users prefer trying to improve cognition by manipulate the object instead of computing in their brain.

Ryall et al. [26] explore the effect of table size and number of collaborators on collaboration. They found that even larger groups were successfully able to manage work on a small table. In order to avoid interference, collaborators usually separated the workspaces based on their seating position and the task semantics [38].

Finally, Scott et al. [29] took a closer look at how territoriality affects collaboration in tabletop workspaces. They found three types of territories: personal, group, and storage territories, and it is important to study handoff techniques to better help participants to transfer and access the resources. *Personal space* usually exists in front of the person. Personal spaces are particular table areas only for their owners' usage. *Share space* usually is in the center of the table and surrounded by personal space. Share space is primarily used for collaborative tasks, to share artifacts and to transfer object between collaborators and between personal spaces. *Storage space* is used to store the tools and artifacts at various locations on the tabletop. Compared with other spaces, storage space is mobile on the tabletop area at different stages of the task.

Figure 13: Users are using Storage Bin on the tabletop system (Table taken from [28])

Scott et al. [28] further improve storage area on the tabletop by Storage Bin. Storage bin's adjustability in size and shape allow people to share and transit resources. The mobility of the storage bin allows users to easily move a collection of stored items in and out of the current territory. People can dynamically resize their working area by expanding or collapsing the storage bin. Figure 13 shows that users are using Storage Bin to sort pictures on the tabletop system.

Transfer Techniques

Due to the size of a tabletop display [26], the sender and the receiver might not be able to reach each other. It is difficult to transfer objects hand-by-hand. Thus, many researchers have also investigated interaction techniques for long-distance reaching and remote object manipulation which is a possible solution for long distance transferring objects on tabletops. For example, *Pick-drop* [2, 23]: A user can select an object by touching and lifting it to pick and drop the digital object with a pen. *Slingshot* [7]: When the pen touches the object, without losing contact with the surface the pen is moved backward and forward, but the object moves toward opposite direction. *Pantograph*: The Pantograph technique is similar to the Slingshot. Instead of toward opposite direction, the object follows the direction where user moves. The further the object is moved, the further it will be thrown toward. *Press-and-Flick*: In this technique the pen pressure and stroke direction determines where and how far the object will go. *Radar View*: a map of the surrounding environment is shown near the selected object. Instead of moving to the real target, the user can access the target with the representation inside of the map. *Tractor Beam*:

It is a remote pointing technique where the distant target can be reached by extending the stylus' pointing direction on the tabletop [11], and control the tabletop object by the remote point. *Drag-and-pop*: [2] It allows users to bring a set of distant candidate targets toward the user. Then users will complete drag-an-drop interactions in a relative short distance.

Another solution for long distance transferring is the handoff action. Handoff is one of the mechanics of collaboration identified by Pinelle et al. [21], and users need techniques for accomplishing handoff actions in tabletop workspaces. There are a number of factors that affect handoff.

First, Ryall et al. [26] found that every user has a certain private work area, and it seemed rude to take objects directly from this space, even with the owner's permission. Users were reluctant to grasp objects that were near their partner, even when these were within their reach. Instead, they asked the partner to first pick up and handoff the object. Ryall also found that although several long-range pointing techniques can solve the privacy problem, users greatly prefer to manipulate objects directly on the tabletop, even if this means asking other users to take part in the transfer [26].

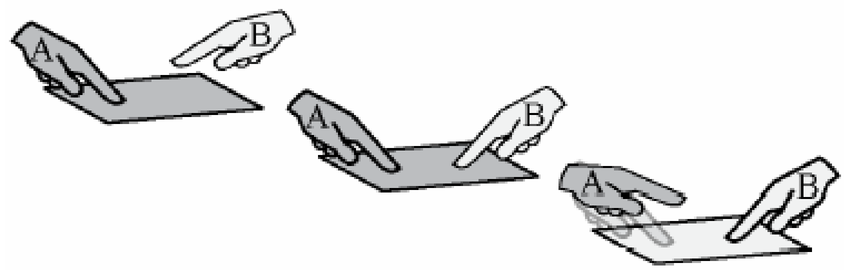


Figure 14: The "release" technique for sharing: Receiver (B) attempts to take the document from sender (A). Sender releases the document to let receiver access it. (Figure taken from [25])

Ringel et al. [25] devise several gestures to support transferring object on tabletop system for collaborative work. This research found that a frequent action on the tabletop was transferring object from a personal area to a public area, so that another person could then move the object into their own personal area (shown at figure 14). This observation follows Scott et al.'s [30] guideline that the transition between personal and shared areas must be protected in the design of interactions for tabletop systems.

Finally, Sallnas et al. [27] investigated handoff in a virtual environment with and without haptic feedback. They found that the time required for passing objects did not differ significantly between the haptic and non-haptic conditions, however, the error rate was significantly lower with haptic feedback.

Although handoff is common in real world tabletop, little thought has been given to its design in digital tabletop system. Studies of real-world tabletop activity have been carried out (e.g., [13, 17]), but there is still little understanding of the various factors that influence handoff. In the next 3 chapters we investigate, through a series of experiments, various factors that influence the design of digital handoff technique and propose new handoff techniques.

CHAPTER 3

OBSEERVATION STUDY ON OBJECT TRANSFER|

Observation Study

We wanted to know how to design digital tabletop systems to support object handoff. Observing people real-world activities was a common way to get that kind of knowledge. We recorded several real tabletop tasks and focused on the handoff actions [22].

Some tasks that belonged to highly collaborative situations were included. We also included several tasks in-order to eliminate any task related bias in our results. These tasks had different collaboration requirements (see Table 3-1) based on the amount of physical coordination and communication demand. The level of physical coordination was dependent on how much users need to negotiate to access tools and supplies; and the level of communication is judged by how much users need to plan and choose their activities.

Table 3-1. Overview of tasks (Table taken from [22])

Task	Physical Coordination	Communication Demand
Stencils	High	Low
Storyboard (large)	High	High
3-D puzzle	Moderate	Moderate
Storyboard (small)	Moderate	High

The study was conducted on a rectangular table (62 in x 49 in). Two groups of participants carried out each task, and each group had 3 or 4 people. A total of 26 people participated in the study, and each person participated in only a single session. Session length ranged from 45 to 90 minutes. A video camera recorded all the activities during each session, which were analyzed afterward.

Task 1: Stencils. Participants were given a 28in x 22in poster board that had a 35-word phrase on it in block letters with different colors. There were only limited supplies: a pair of scissors, a box of 8 colored markers, a glue stick, a pad of white paper, and a set of cardboard stencils. Users were asked to use the pens to draw the letters on the paper, and use markers to color the letters to match the corresponding color from the board. The users had to cut the letters, and glued them to the corresponding letters on the poster board. The task was complete when all the letters were printed on the board.

Task 2: Large Storyboard. Users were told to cut images from magazines, glued them to a 28in x 22in storyboard, and added their comments to the images with pens to create a story. There were a stack of magazines, a glue stick, a set of markers, and a pair of scissors. Users were asked to look through the magazines and look for some images to tell a story.

Task 3: Constructing 3D-puzzle. There were 327 pieces of a 3D puzzle spread on the table and the users had to reconstruct the puzzle (a famous church from Barcelona). Users were also provided with a sheet that described the instruction for reconstruction.

Task 4: Small Storyboard. It was similar with the storyboard task described in task 2, but the storyboard was cut into four smaller (14in x 11in) pieces.

Observation Results

The proceedings of each session was captured on video and analyzed later. The video analysis focused on tool/ artifact transferring actions and the surrounding context. We counted the number of transfers and categorized each transfer as deposit or handoff. Asynchronous actions that took more than 15 seconds were considered as two independent reaching tasks and were not counted. In the case when the sender placed an object at a certain location for the receiver to pick-up, the asynchronous action was considered a deposit only if the total transferring time was less than 15 seconds.

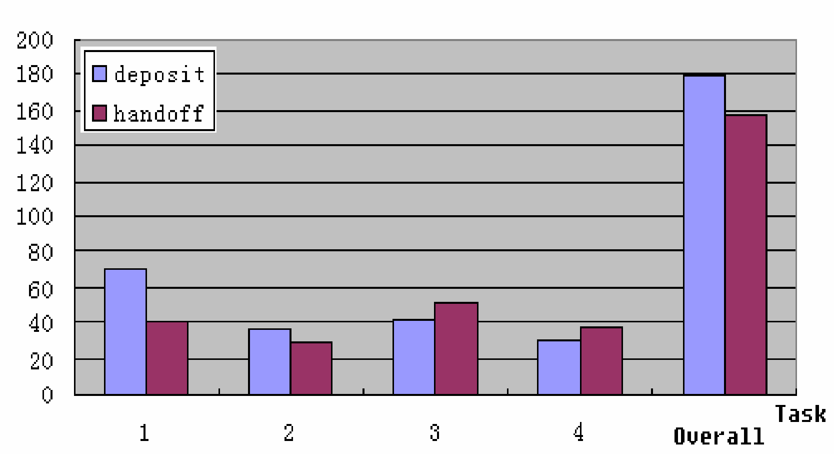


Figure 15: Number of handoff and deposit for 4 tasks and overall.

We found that object transfer was an important activity in these tasks. On average users transferred 0.85 objects per minute. Participants frequently used both deposit and handoff to accomplish the transfer; both deposit and handoff need a lot of coordination and collaboration between the sender and the receiver. Figure 15 shows the distribution of handoff and deposit for each task. On average users used handoff to transfer the object 46.7% (157 of 336).

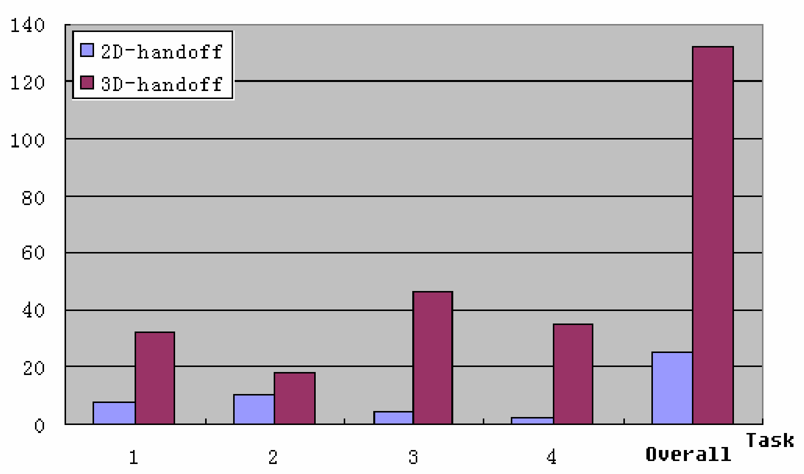


Figure 16: Number of 2D-handoff and 3D-handoff for 4 tasks and overall.

We also found that users typically employed two strategies to handoff objects. On some occasions users restricted their tool-transfer to the surface of the table whereas in most other cases they used the 3D space above the table to facilitate handoff. Figure 16 shows the number of 2D and 3D handoffs per task. Overall in 132 of the 157 handoffs, participant used the 3D-handoff technique.

Task 3 (3D-puzzle) had the highest percentage of handoff (55.4%). We believe the reason for this is that the workspace was littered with many groups of pieces belonging to different part of the puzzle and deposit would have resulted in confusion between sender and receiver. The receiver would have needed to remember the exact shape, identify and handoff location of the object to pick-up the object. Thus, deposit increased the user's effort to finish the transfer whereas handoff did not suffer from these limitations. For similar reasons users preferred to use 3D-handoff over 2D-handoff. In both task 3 and 4, 3D-handoff was preferred more than 90% of the time over 2D-handoff.

The Users' Roles for the Handoff

The handoff action is a complex task which needs high coordination and communication. Through our observation, generally speaking, there are three stages and three user roles for the handoff action; and besides those, users must also use communication and coordination actions to help them better handoff objects.

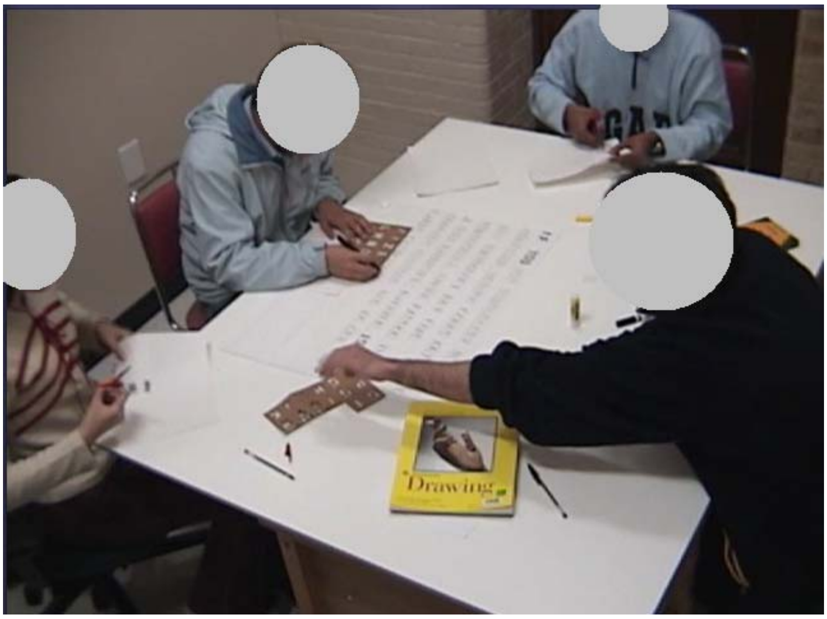


Figure 17: The role of initiator (the person on the right edge of the table) during the handoff action.

The users' roles for the handoff are important, because the role of the user in the handoff action determines what and how he will transfer the object. We find three kinds of user roles in our observations: initiator, follower and observer.

Initiator: the person who initializes the handoff action. Firstly, the initiator finds a special object which is valuable for him or the other collaborators. Then he starts a conversation with the person who will be benefited or who can easily access the object. During the conversion, the initiator will specify to the person who will do the handoff action with him: which object should be handed-off, why the object is useful and how the object will be used after the handoff. Of course, the initiator is not always right; during the conversation, the other collaborators can argue with the initiator, until all of them agree to start a handoff action or cancel the handoff proposal. The initiator can be either the sender or the receiver. As shown in figure 17, the person who sits at the right side of the table is the initiator. He spreads his arm out, points and acquires a piece of paper from the person who sits at the bottom left corner of the table.

Figure 18: The follower (on the bottom left edge of the table) helps the initiator to handoff the object.

Follower: the person who help the initiator to do the handoff action. Usually, the follower is interrupted by the initiator's handoff proposal. Then, the follower will communicate with the initiator to fully understand everything for this handoff; or does not care about the reason for the handoff and just simply passes the acquired object to the initiator. Of course, during the communication, the follower can disagree with the initiator or propose another object for the handoff action. The follower can be either the sender or the receiver as well. As shown in figure 18, after the conversation in which the object is acquired, the follower who sits at the bottom left corner of the table was interrupted by the initiator's requests, and he stops his own task and passes the object to the initiator.

Observer: the other persons who are neither the sender nor the receiver for the handoff action. Observer will not be interrupted by the initiator; he can overhear the initiator and the follower's conversation. The observer can join the discussion to give his own opinion, however he will not participant in the handoff action process.

After we analyze the user roles for the handoff, we focus on what and how these user roles join the handoff action process. As shown in figure 19, the handoff action includes three stages: retrieve the object stage, handoff the object stage and move the object toward the target stage. We use block arrows to indicate the timeline sequence for these three handoff stages. And there are communication and coordination actions as well to help the sender and receiver to successfully achieve these three stages. We use arrow lines to represent which handoff stages communication and coordination are applied to.

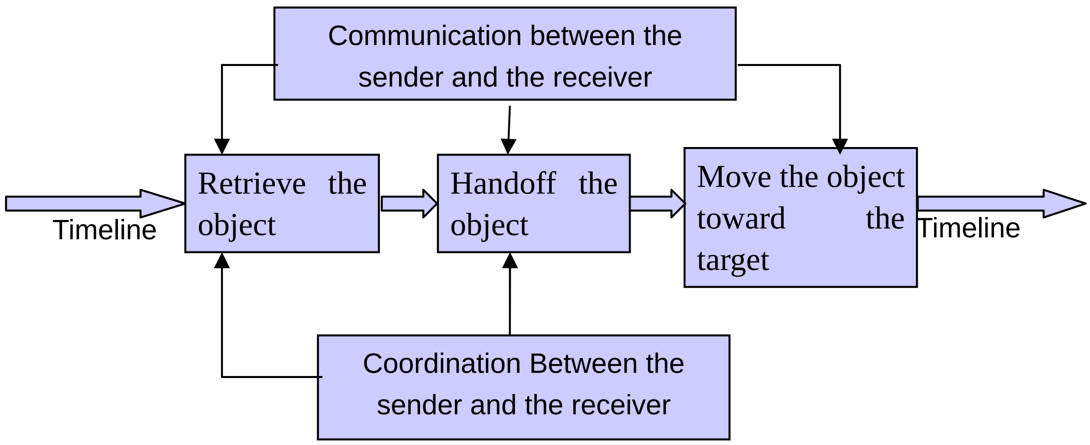


Figure 19: The stages of handoff action.

Figure 20: Stage 1 of the handoff action.

Retrieve the object stage: The sender takes more responsibility during this stage. The sender picks up the object and moves it towards the receiver. Usually before that, the sender and receiver communicate with each other to make sure both of them fully understand why and how the handoff action will happen. Figure 20 shows that after the discussion, the initiator (on the left edge of the table) is pointing to the object and asking the follower (on the top edge of the table) to the pass the object to him. The follower picks up the object and moves it toward the initiator. They are coordinating their actions with each other to let the receiver grasp the object as quickly as possible.

Figure 21: stage 2 of the handoff action.

Handoff the object stage: Both the sender (on the top edge of the table) and receiver (on the left edge of the table) take responsibility during this stage. When the sender moves the object towards the receiver, the receiver also adjusts his movement toward the sender until both of them can grasp the object at the same time. Then the sender releases the object and notifies the receiver by verbal communication that the object is transferred; or the receiver can feel that the sender has release the object and he is the only person in control the object. Finally, the sender and receiver's hands move far from each other. The coordination action is needed for the sender and the receiver in order to move the hand and the object to meet the other person's hand or the object as quickly as possible. Figure 21 shows that the sender and the receiver is handing-off the object. They communicate while coordinating with each other to let the sender know that the receiver has grasped the object and to let the receiver know that the sender has released the object.

Figure 22: stage 3 of the handoff action. (The 3D house on the bottom left side of the table is the target.)

Move the object toward the target stage: The receiver (on the left edge of the table) will take more responsibility during this stage. The receiver keeps moving the object towards the target that was proposed before the handoff action. When the transferred object arrives at the target, there might be a conversation between the sender (on the top edge of the table) and the receiver to discuss whether it is a right proposal. Figure 22 shows that after the object is transferred, the receiver is moving the object toward the target and trying to match the object with the current 3D puzzle architecture.

Figure 23: the communication is held between the sender (on the top edge of the table) and the receiver (on the left edge of the table).

Communication action: As we explained in the three user roles and three stages, communication has an important influence for the handoff action. The initiator can explain the propose of the handoff by communicating with the followers, and let the followers and observers fully understand the detailed information about this handoff action, notify the receiver when the object is transferred to him, and discuss the correctness of the proposal of this handoff action. Figure 23 shows that the sender and the receiver are discussing the fitfulness of the transferred object to the current 3D framework.

Coordination action: The coordination action also is critical for the handoff action. In order to handoff the object faster, both the sender and receiver has to coordinate their movement to meet the other person's movement. In order to notify the receiver the object has been handed-off, both the sender and the receiver have to coordinate their strength applied on the object during the handoff action.

Generally speaking, all these components are important for the handoff action procedure. Without clearly identifying and separating them, it is hard to do further study. Next, we are going to continue discussing some interesting issues found from the observation.

Discussion

Here we discuss the various factors we could identify that influence handoff.

(a) (b)

Figure 24: Handoff point is between sender and receiver

Sender and receiver's Positions:

In a standard tabletop collaboration environment, the receiver has three possible positions - right, top and left side of sender. We found that users most often choose the shortest route to handoff the object (see Figure 24 for stereo-typical examples). Wherever receiver and sender maybe seated, the handoff point is always distributed near the route between sender and receiver. The distance between object and target also influenced the handoff action; for long-distance transfers, senders found it difficult to reach the receiver and therefore performed a deposit to transfer the object. We found that handoff actions between two persons who sit near each other come about on 89 out of 157 occasions. We considered participants to be near each other when they were approximately as close as the adjacent participants in Figure 24.

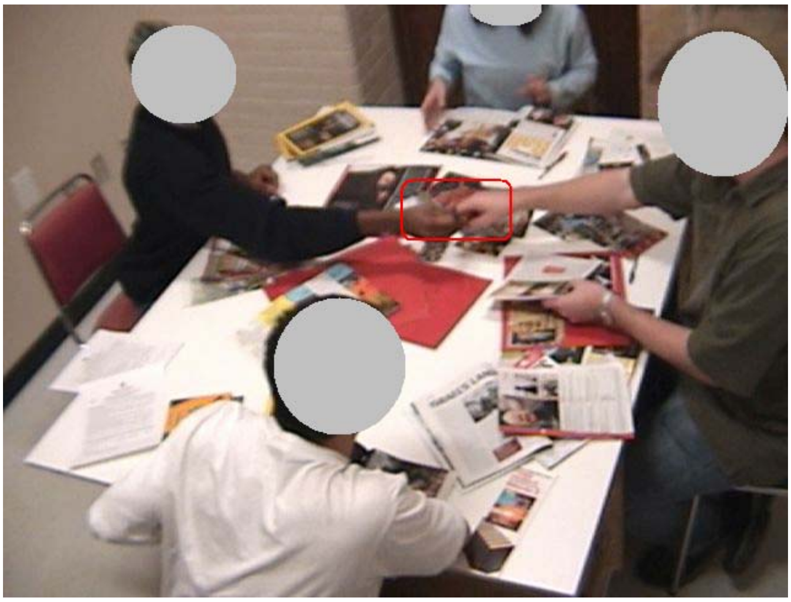


Figure 25: Handoff and rotate object

Object orientation.

In the tabletop environment, the orientation of the object has a lot of meaning to everyone sitting around the table [9]. Since handoff needs coordination between multiple participants, collaboration will be different depending on the object's orientation. Because the receiver already knows how to use the object, he will grasp the part of the object in a way that is easy to transfer as well as comfortable to use after the transferring. If the sender transferred the object in an inappropriate orientation, the receiver has to do some adjustments after the transferring. Figure 25 shows an example: the user sitting on the left side of the table was passing scissors to the person on the right side. The sender rotated the scissors before negotiating its handoff with the receiver. The receiver could easily grasp the scissors handle and immediately cut the pictures from magazines.

Figure 26: Action awareness after the handoff

Awareness of others' actions:

One of the difficulties with handoff is that the sender and receiver do not fully acknowledge how the other person will deal with the object before and after the handoff. Sometimes, the handoff object can even interfere with the receiver's current task (see Figure 26 (a) for an example). We found that when the sender and receiver could provide more information to each other, the sender comprehends and predicts the other's actions and adjusts his own actions to handoff object in a better time and place for the receiver. In figure 26 (b), the person sitting on the left side of table is aware that the receiver (standing on the top end of the table) will reference the puzzle-assembly instructions on the box, so he handed-off the box in front of the receiver’s hands and did not interfere the receiver’s work on his personal area. So the receiver can quickly get the box and, at the same time, continue doing his work.

Figure 27: handoff between personal areas

Territoriality and privacy issue on the tabletop.

The territory on the tabletop can be subdivided into personal space, shared space and storage space [4, 29]. Handoff action seldom occurred inside a personal territory without permission of the owner. Senders always picked up the object from their personal territory, moved it to the shared space and waited there for the receiver to pick it up. However, if sender and receiver communicated with each other and agreed on the task to do, sometimes handoff happened in the sender’s personal space. We found that there were 137 handoffs outside of personal area of a total of 157 handoffs. Figure 27 illustrates this handoff scenario. The red circle emphasizes each user’s personal area. The size of the red circle is determined by the collaboration context and expert experience. The participant seated to the right wanted the scissors that were located in personal area of the person seated at the top. So he asked the scissors’ owner, and then they used a handoff action to transfer the scissors. Even when users were seated near each-other most handoffs occurred in the shared space between the users and not in the personal space of any user.

Figure 28: 2D-handoff action on the tabletop

Handoff techniques

Good techniques will not only make the user perform better on translation and/or rotation of objects, it will also make the user interact in the same way that they interact with physical objects on the tabletop. On the other side, a bad technique will make it difficult to control the object, which will cause a lot of extra workload for sender and receiver. Therefore different handoff techniques will make users perform differently on the handoff action. Based on our video observations, the technique of handoff is determined by the nature of the task. If a task requires people to transfer objects accurately among each other, people tend to use handoff. If a user wants to do a quick translation without interrupting other people, he will choose deposit. (People even combine other technique, such as flick with the deposit to make the translation faster). Based on our observation people prefer using 3D-handoff, because the passing object will not be mixed with items on the tabletop and 3D-handoff will not interfere with other people. However, sometimes people use 2D-handoff if it does not cause any problem. Figure 28 shows two people performing a 2D-handoff.

Summary

By observing people doing tasks on tabletop, we found some guidelines which can help people design the tabletop system, including Sender and receiver's Positions; Awareness of others' actions; Territoriality and privacy issues on the tabletop and Handoff techniques.

Although studies of real-world tabletop activity have been carried out (e.g., [15, 16]), there is still little understanding of the various factors that influence handoff. Two issues in particular that are not well known are: the factors that affect handoff location (the location on the tabletop where the sender hands over the object to the receiver); and the factor affecting handoff time (the total time taken to complete a handoff task). Likely features include the visibility of the final target (for the sender) and the position of the receiver with respect to the sender. To study these issues in more detail, and to get a better understanding of other factors that could help to design handoff techniques for digital tabletop systems, we conducted a quantitative evaluation on handoff techniques.

CHAPTER 4
INVESTIGATING 2D-HANDOFF

Introduction

Through the observation study, handoff was proved to be a frequent and important action of the tabletop interactions. Since most of the current digital tabletop systems are touch based, users have to keep their stylus or finger on the surface of tabletop to get the input. This fact makes users have to use 2D-handoff to transfer objects. So, this chapter focuses on studying different techniques and mechanisms for 2D-handoff. Any references to “handoff” in this chapter correspond to 2D-handoffs. Firstly, we carried out a pilot study comparing a tangible block handoff technique with the standard digital pointer handoff technique. Based on the findings from the observational study, we varied target size, location and target visibility for sender in the pilot study and tried to find out whether these variables affected the different handoff techniques. Secondly, we invented an improved digital handoff technique, called force-field technique. We were going to compare this force-field technique with traditional handoff technique and tangible handoff technique and try to demonstrate the force-field is better than traditional technique.

Study of Handoff Techniques

Apparatus

A top-projected tabletop display (155cm x 111cm) was used as the work surface. The transfer techniques were implemented using a Polhemus Liberty system, with the sensors attached either to the tangible block or to the participants' fingers.

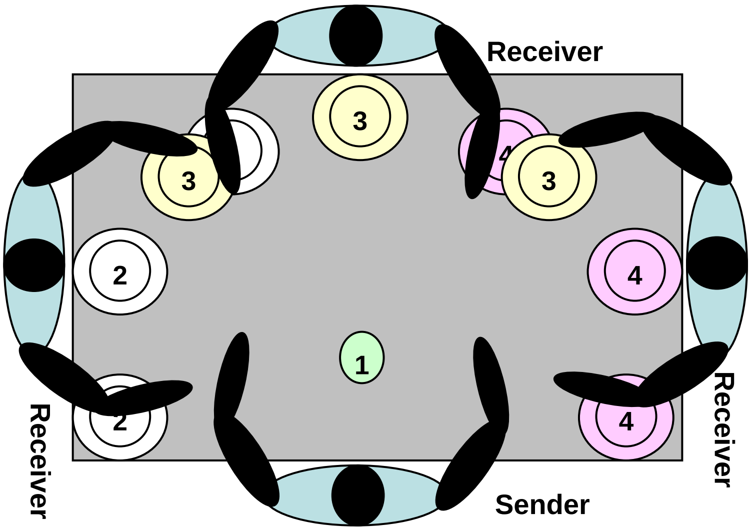


Figure 29: Top View of the Experimental Setup

Task

Each trial was conducted with two users: a sender and a receiver. As shown in figure 29, there is only one start point of object (position 1) and only one position for the sender (bottom side of the table). There are three possible positions for the receiver (right, top and left side of the table) and at each receiver's position, there are also three possible target positions (dominant, middle and non-dominant side) for big and small targets (position 2, 3 and 4).

The sender was instructed to select a digital circular object of radius 6 cm (40 pixels) from a start position, and transfer it to the receiver, who was instructed to move it to a target. The targets were circular icons of varying sizes distributed on a circle which has 70cm radius from the object. Once the object was moved from the start position, it could not be 'dropped' – either the sender or the receiver had to always have the object selected. The trial was completed when the receiver placed the object in the target. Subjects were asked to perform repetitions of the task for the two different handoff techniques, as quickly as possible. Audio feedback was given to the users when the object was acquired, transferred, and placed inside the target.

Handoff Techniques

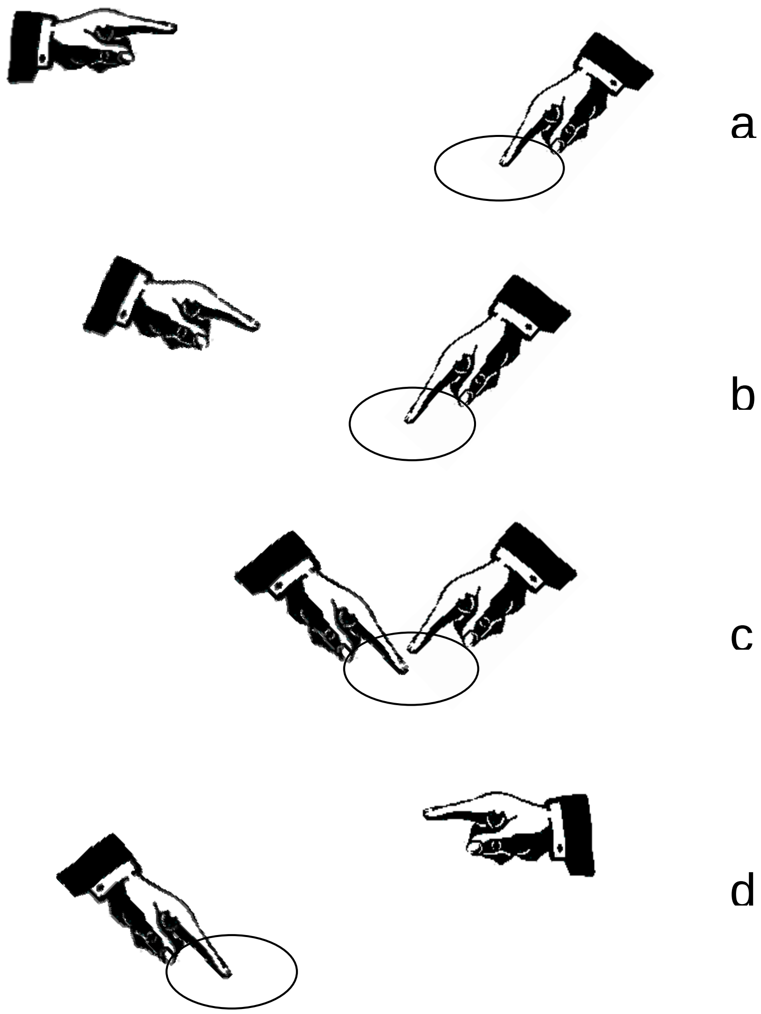


Figure 30: Digital handoff technique

Digital handoff This technique is similar to how handoff is implemented in many current tabletop systems. Here, sensors were attached to both users' index fingers to allow users to point to and select objects on the tabletop. The object is selected by touching the finger on the object; the object then follows the finger's movement until the user lifts his finger from the table surface. In this technique, handoff occurs when the receiver touches an object that is controlled by the sender (see Figures 30 a, b, c and d). Unlike some digital handoff implementations, the sender did not have to release the object in order for the receiver to start moving; that is, the technique worked on a 'last-touched' principle.

Tangible block handoff This technique is a variation on the media block technique [40]. A sensor was attached to a cardboard 'block' that was the same size and shape as the digital object. Digital objects could be picked up by sliding the block onto the object; when the block was on top of the object, it would become selected and could be moved by moving the block. To transfer the object, the sender and receiver transferred the physical block; the receiver then moved the block (and the object) to the target location. Participants were asked not to pick up the tangible block, but rather to slide it across the table.

Experimental Design

The experiment was conducted with 8 participants organized into 4 pairs (2 male-male pairs, 1 female-female pairs, and 1 male-female pairs). All participants were right-handed, and were between the ages of 23 and 35. People played both roles in the study: first one person would be the sender and the other the receiver; they would then repeat the experiment in the other role.

The experiment used a 2x2x3x3x2 within-participants factorial design. The factors were:

- Handoff Technique (Digital or Tangible)
- Target Size (radius 7cm or 16cm)
- Receiver Position (Left, Center, or Right)

- Target Position (dominant, middle and non-dominant side of each receiver position)
- Target visibility to sender (Visible or Not visible)

Each pair completed 12 training trials per technique and 4 test trials per factor (for a total of 288 test trials and 24 training trials).Upon completion the users switched roles.

The handoff location, handoff time and total trial completion time were recorded per trial. The study system recorded all data, except in the case of the tangible technique, in which the time of the handoff event was manually recorded by the experimenter (using a key-press).

Results

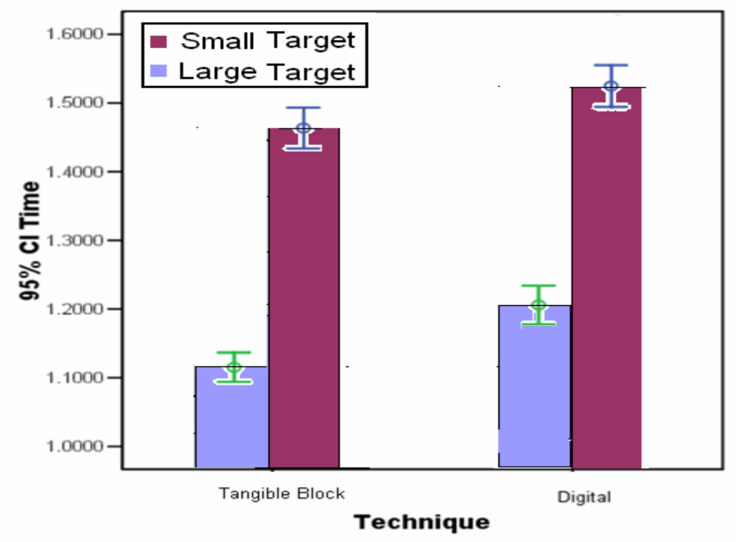
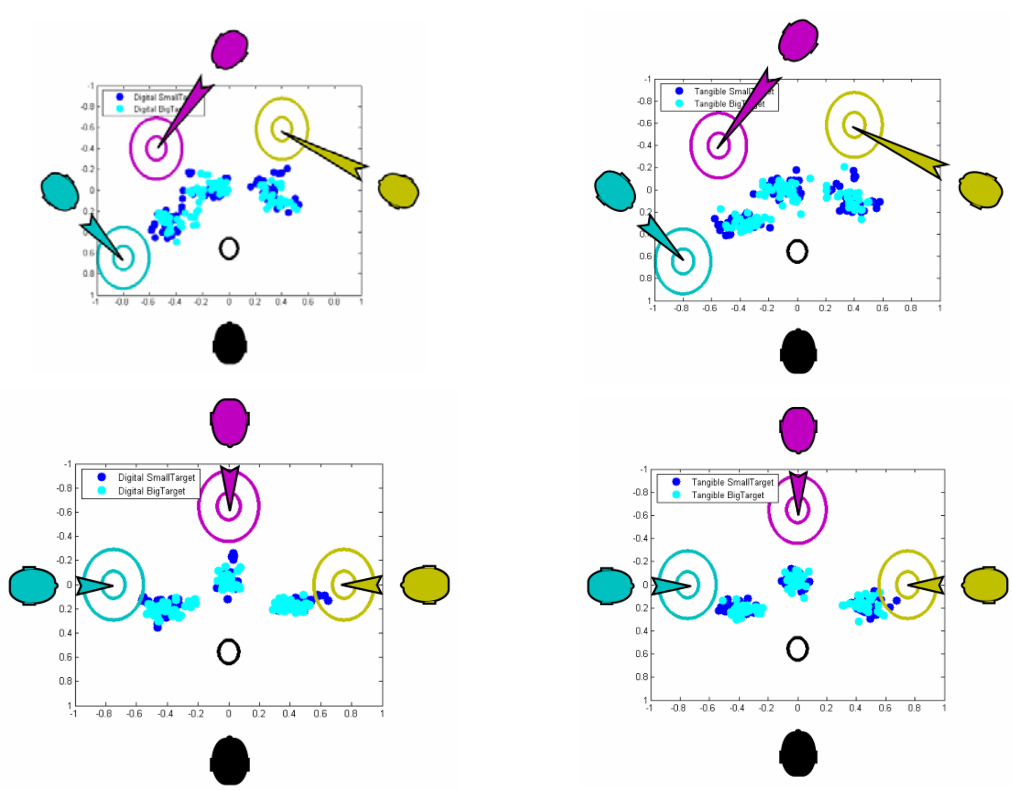


Figure 31: Average Handoff time with 95% confidence intervals for each interaction technique.

We used two performance measures: completion time and handoff-to-target distance. Handoff-to-target Distance measures the distance between the handoff location and the target. It gives a measure of how far the sender and receiver each moved the object.

Completion Time:

The overall mean handoff time was 1.41 seconds (standard deviation of 0.4 seconds). 2x2 repeated measures ANOVA showed main effects for both factors (interaction technique and target size). For interaction technique F (1,143) = 21.43, ($p<0.001$) and for size F (1,143) = 874.7 ($p<0.001$). Figure 31 shows the average handoff time with 95% confidence intervals for the different interaction techniques clustered by target size. It shows that tangible handoff was faster than digital handoff in the case of both larger and smaller targets by 0.09 (about 8%) and 0.06 (about 5%) seconds respectively. Although the actual difference is small, in the case of large targets, the difference is significant ($p<0.001$). In addition, large targets were significantly faster than small targets by 0.35 seconds.



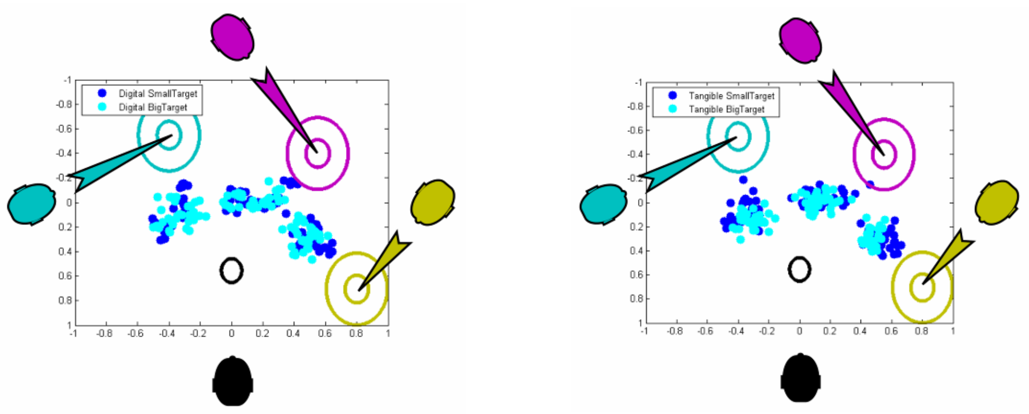


Figure 32: Distribution of handoff points for visible target by digital technique (left) and tangible technique (right).

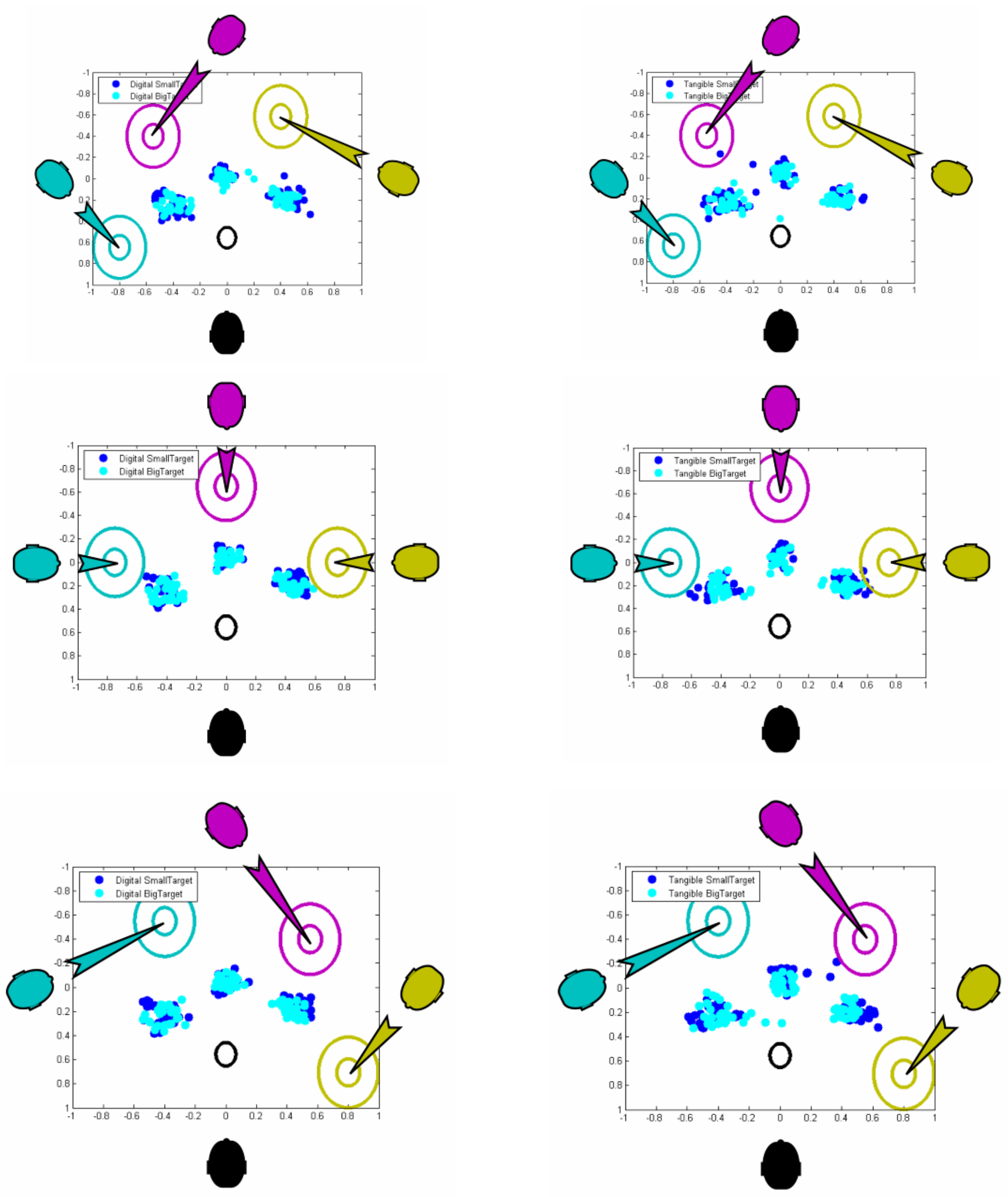


Figure 33: Distribution of handoff points for invisible target by digital technique (left) and tangible technique (right).

Handoff-to-target distance:

The overall mean handoff-to-target distance was 38cm (standard deviation of 8cm). The total distance between sender and receiver was fixed experimentally at 70 cm in all conditions. A 2x2 repeated-measures ANOVA showed main effect for target size $F(1,143) = 126.3$ ($p<0.001$). We did not see any effect of interaction technique on handoff location. Figure 32 shows the distribution of handoff points for different target and receiver positions by digital and tangible technique. We did not find any clear pattern in the handoff locations for any of the interaction technique. The left column was for digital handoff technique when the target was visible for the sender. And the right column was for tangible handoff technique when the target was visible for the sender.

Target Visibility:

There was no effect of target visibility on handoff times for both interaction techniques and target sizes. There was a slight increase (significant at $p<0.05$) in handoff-to-target distance when the target was invisible. Comparing figure 32 (digital and tangible technique with visible target) with figure 33 (digital and tangible technique with invisible target), one can see that in the case of invisible targets the sender tends to assume that the target is right in front of the receiver and tries to move the object towards that location. The left column was for digital handoff technique when the target was invisible for the sender. And the right column was for tangible handoff technique when the target was invisible for the sender.

In figure 32 and 33, we only show the situation that the targets were on the dominant side of the receivers. There are the similar patterns of the handoff points' distribution for targets on the middle and non-dominant side of the receivers.

Mechanism of Handoff

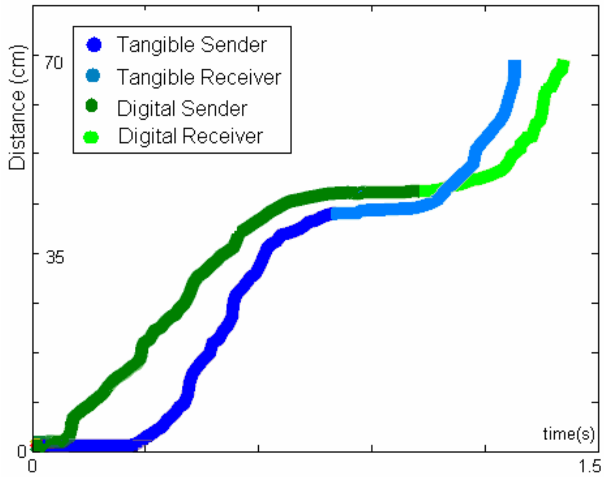


Figure 34: A typical path traced by the object from start to finish for each technique. The first part of the trace is by the sender and the second by the receiver.

Figure 34 shows a typical path traced by the object from start to finish for each of the handoff technique for larger target. The first half of the path was traced by the sender and the second half by the receiver. Closer analysis of the figure reveals that negotiating the handoff is the bottleneck in both the tangible and digital handoff. The movement speed of object has to slow down when the sender is transferring object to the receiver. By using the tangible handoff technique, the object can be easily and quickly transferred to receiver, but with the traditional digital handoff technique, it needs more time for sender and receiver to coordinate with each other before the object can be handed over to the receiver.

The pilot study and figure 34 show that digital handoff techniques can be improved by reducing the complexity of negotiating the actual transfer between sender and receiver. Thus, the next section will discuss an improved traditional technique, force-field handoff technique. And we also run an evaluation to prove that force-field technique indeed performs better than traditional handoff technique.

Improved Handoff Technique

Force-field Handoff

We developed a new handoff technique, called force-field technique that meets some design goals. Force-field handoff simplifies the transfer between sender and receiver by making the size of the object bigger as the sender's and receiver's pointers approach each other. To accomplish this, we created a 'force-field' region around the object so that when the receiver's finger approaches the object (within thrice its radius) the object starts drifting towards the receiver along the direction in which the receiver's hand is approaching (see Figure 35 a, b, c and d). This increases the effective width of the object and reduces the distance the receiver has to move to acquire the object.

The object, however, does not get transferred to the receiver until he moves into the object and clicks or keeps his finger on the tabletop and moves into the object. Either of these actions results in the object getting transferred from the sender to the receiver.

If the receiver does not take any of these actions the object deforms but does not automatically initiate a handoff. If the receiver ignores the object, the sender retains control of it. Similarly, if the receiver moves out of the force-field zone without taking action on the object, it drifts back to the sender's pointer. This prevents accidental handoffs in situations where the sender is merely depositing or reaching with the object at the same time that a second user carries out a near but independent action.

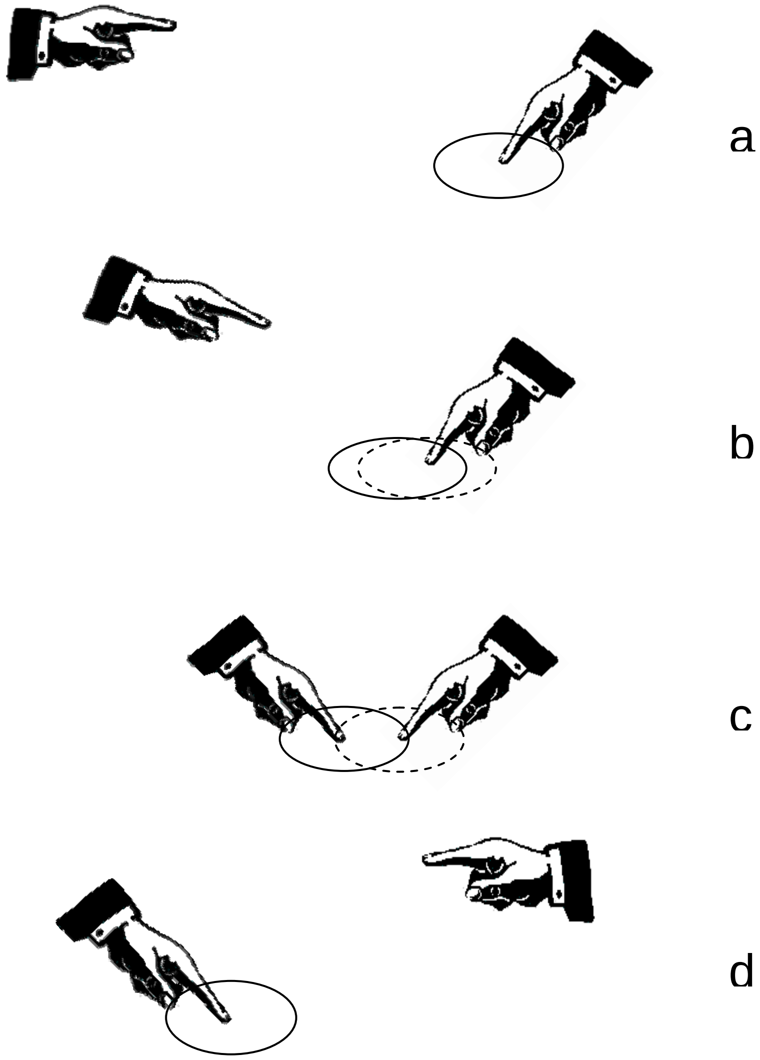


Figure 35: Force-field Handoff Technique.

We conducted an experiment to compare the force-field handoff technique with tangible handoff and traditional digital handoff techniques. The experiment was conducted with different target sizes and position with a large enough sample population to perform significance tests.

Experimental Design

The apparatus and experimental task were similar to the pilot study. The experiment was conducted with 8 right-handed pairs (4 male pairs, 2 female pairs and

2 male-female pairs) between the ages of 18 and 40. For each pair one user was the sender and the other one was the receiver. The experiment used a 3x2x3x3 within-participants factorial design with a variety of planned comparisons. The factors were:

- Handoff Technique (Digital, Force-field, Tangible)
- Target Size (radius 7cm or 16cm)
- Receiver Position (Left, Opposite and Right side of sender)
- Target Position (dominant, middle and non-dominant side of each receiver position)

Each pair completed 12 training trials per technique and 4 test trials per factor (for a total of 216 test trials and 36 training trials). Upon completion the users switched roles

After the session, participants were asked to state their preference between the three techniques. The handoff location, handoff time and total trial completion time were recorded per trial. The study system recorded all data, except in the case of the tangible technique, in which the handoff event was manually indicated to the system by the experimenter (using a key-press).

Results

We used three measures: handoff-to-target distance, total time and subjective preference.

Completion Time

The overall mean completion time across all conditions was 1.47 seconds (standard deviation of 0.38 seconds). A 3x2 repeated measures ANOVA showed main effects of both factors (technique type and target size). For technique type, $F(2,142) = 13.05$ ($p<0.001$) and for target size $F(1,143) = 179.1$ ($p<0.001$). As can be seen in Figure 36, the force-field technique was faster than the digital technique. In addition, small size targeting was always slower than large size targeting.

There was a small but significant interaction between technique type and target size $F(2,142) = 3.08$, $p<0.05$. As shown in Figure 36 there was a bigger difference in handoff times between larger and smaller when using the tangible technique.

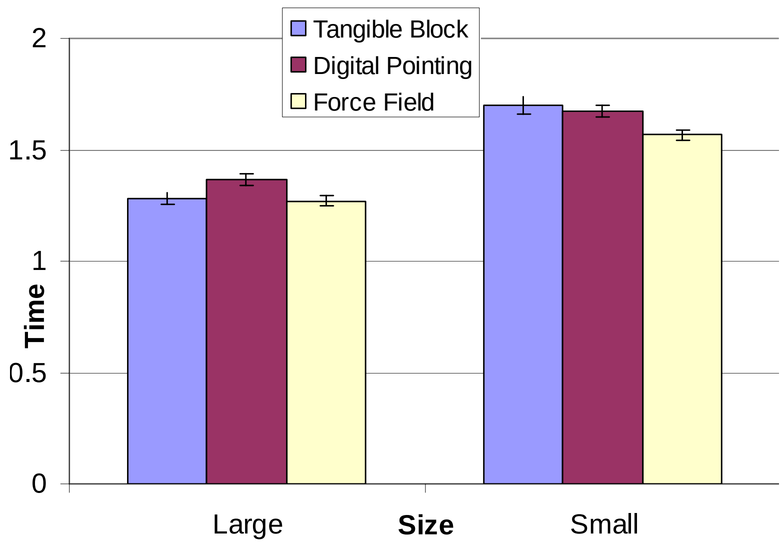


Figure 36: Average Handoff time with standard error 95% confidence intervals for each interaction technique.

A post-hoc pair wise comparison of the interaction techniques showed that force-field is significantly faster than digital handoff for both small and large targets. The force-field and the tangible technique were not significantly different for large targets.

There was no effect of different receiver positions on handoff time. However, we found that for large targets handoff was significantly faster ($p<0.002$) when the receiver was on the right side of the sender than on the other two positions.

Handoff-to-target distance

The overall mean handoff location across all conditions was 39cm (standard deviation of 10.6cm). 3x2 Analysis of Variance (ANOVA) showed main effects of both factors (technique type and target size). For technique type, F (2,142) =8.67, $p<0.001$; for target size F (1,143) =104.197, $p<0.001$. Force-field and tangible handoff happened significantly closer to the sender than digital handoff.

A posthoc pair-wise comparison of the interaction techniques showed that for larger and smaller targets there was no significant difference in handoff-to-target distance between tangible technique and force-field technique.

Handoff-to-target distance for small size targeting was always smaller than large size targeting. When targets were larger, handoff happened about 4 cm closer to the sender than when targets were smaller.

There was no effect of receiver position on handoff location. There was also no difference in handoff locations for the three different targets of each receiver position.

Subjective Preference

After each task participants were asked to rank each technique based on their perceived speed, accuracy and overall preference. Each technique was assigned a number between 1 and 4 with 1 being best and 4 being worst. Force-field handoff was the most preferred technique in all categories. Figure 37 shows the mean value for the ranking of each technique.

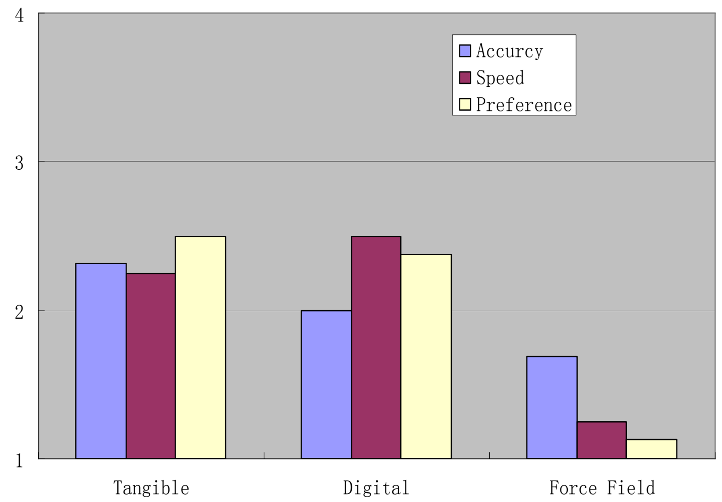


Figure 37: Average user preference scores for each interaction technique.

Discussion

Negotiating Handoff

Figure 38 shows a typical trace of handoff path using the three different techniques. It highlights how the force-field technique alleviates the bottleneck in negotiating handoff. The main benefit of this technique is that users don't have to stop moving the object to negotiate handoff, they momentarily slowdown to allow the object to drift from the sender to the receiver.

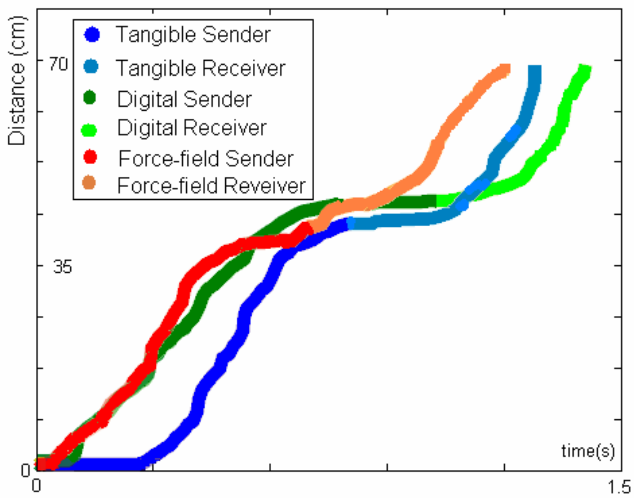


Figure 38: A typical path traced by the object from start to finish for each technique. The first part of the trace is by the sender and the second by the receiver.

Since handoff can happen within the force-field region, both sender and receiver need not pay much attention to find out where the object is or whether their pointer was inside the object to click to complete handoff. They mostly paid attention to each others hand location rather than to the object itself.

Force-Field Technique

Performance using the force-field technique was comparable to the tangible technique, and users preferred the force-field over other techniques. The main benefit of the force-field technique is the way in which the object drifts towards the receiver. The drift region is big enough to make a significant difference in negotiating handoff without affecting other tasks on a tabletop.

An important advantage of this technique is that it is associated with the object not with the input device. So it can not only work with different input device but also, based on context, work differently for different objects. For example, frequently transferred digital documents can have larger force-field zones and private documents can have negative zones to make them harder to handoff.

Tangible Handoff

Tangible devices allow users to perform handoff using their well-learned real-world skills. However, using tangible devices may not be convenient for all situations. In many tabletop systems where the collaborative task primarily involves pen or finger input, using tangible objects requires additional effort. That is, users have to switch input devices to perform handoff. This adds to the overhead of collaboration and could potentially break the seamlessness of the collaboration.

Furthermore, once a tangible token is used to transfer an object the token has to be returned to the sender to perform another handoff. This doubles the number of transfer when using tangible tokens for object transfer.

Handoff Location

Handoff locations occur at specific distances from the sender and receiver. This distance depends on the interaction technique used and the size of the target. But we did not find any clear pattern in the handoff locations for any of the interaction technique. This makes it difficult to predict handoff locations in different settings.

When the targets are visible to the sender the handoff location varied with target size. There was an intuitive sense of task difficulty that leads to load balancing between the sender and receiver for the different target sizes. As we saw in the first study, this disappears when the sender does not know the final destination of the object.

It is quite possible that under some conditions the most optimal handoff location occurs in one of the user's private space. To support such handoffs, it is necessary to be flexible in defining private and public spaces.

Applicability of Experimental Setup

In our study users were asked perform handoff repeatedly, and the sender and the receiver were both aware that the task was going to be performed in this manner. However, in a collaborative setting, handoff is rarely performed repeatedly within the span of a few minutes.

It is also possible that handoff can be influenced by the person, who requests the transfer of an object. The initiator of the interruption might take on more responsibility during handoff. So if receiver asks sender for an object handoff might occur differently from when sender initiates transfer of object to receiver.

Lessons for designers

Our studies provide several guidelines that can be used by designers of tabletop systems:

- The sender and receiver have an intuitive understanding of the overall workload involved and use that to agree on handoff locations. Our experiment shows that handoff locations occur at specific distances from the sender and receiver. This distance depends on the interaction technique used and the size of the target.
- Allow flexibility in defining public/private space to accommodate the variable construction of handoff. Handoff locations vary with interaction technique and overall task difficulty. It is quite possible that under some conditions the most optimal handoff location occurs in one of the user's private space. To be able to accommodate handoff at these locations the designer should allow flexibility in defining public and private spaces.
- Augment any object or tool that will be frequently transferred with force-fields. Our study shows that handoff is considerably faster and easier with force-field techniques than other digital or tangible techniques.
- If possible, make the sender and receiver aware of the final destination of the target. This allows users to automatically share the overall workload.

Summary

In this chapter, we have done a thorough evaluation of using 2D-handoff techniques to transfer objects for digital tabletop systems. It includes two parts: We first are trying to find out the problems for traditional digital handoff technique by running a pilot study. The results show that, as we expected, the traditional handoff technique does not well support handoff actions on the tabletop workspace. That is because participants need more time to communicate, coordinate and negotiate with each other when the sender hands over an object to the receiver which slowed down the movement speed of the object. By knowing the bottleneck of the traditional 2D-handoff technique, we invented force-field handoff technique which could improve the traditional technique. A user study was run to establish that force-field can help participants to handoff objects faster and with more satisfaction.

CHAPTER 5
3D-HANDOFF TECHNIQUE AND DIGITAL JIGSAW PUZZLE GAME

The previous chapter examined handoff techniques that were restricted to the active work-surface of the digital table. However, the observational study in chapter 3 showed that users often used the surface above the table to engage in handoff actions when working with real-world objects and tools.

Most current digital tables and input sensing techniques only support user actions that are on the active surface of the table. Thus, current systems can only provide 2D sensing data for interaction on the digital table surface during interaction. Recent advances in computer vision and other magnetic tracking technologies make it viable to support low-cost 3D interaction in the near-future. Based on this premise researchers are examining the benefit of supporting user interaction above the active work-surface, such as using such 3D information to create multiple discrete layers for user interaction on digital tables. In this chapter we examine the benefits of supporting 3D-handoff actions in digital tables.

We first developed a 3D handoff technique using a commercial 3D motion tracker. Since there were very few past studies focusing on 3D-handoff techniques it was not possible to do a controlled study to do a speed/accuracy comparison between techniques. We developed a digital jigsaw puzzle game as the task on the digital tabletop environment and tested the various transfer techniques (deposit, 2D-handoff and 3D-handoff) to get ecologically valid data.

3D-handoff Technique

We started with a naïve implementation of the 3D-handoff technique that was based on our observation of how 3D-handoff occurred in the real-world. The sender selects the object with his stylus and moves the stylus towards the receiver. Unlike the 2D-handoff condition, users were not obliged to keep their stylus or their palm on the table. The sender could lift the stylus into the 3D space above the table surface and wait for the receiver to pick it up. To handoff the object from the sender, the receiver had to move his stylus toward the sender's. He had to try to use his own stylus' pin-point to touch the sender's pin-point. Then the object would be handed-off to the receiver when he pressed the button on his stylus.

However, we found that it was difficult to let users achieve 3D-handoff by meeting pen-points of the styluses. Because according to the Fitts' law, it was very difficult to do pointing task when the target was very small, such as pin-point. To alleviate this problem, we applied a virtual sensitive sphere around each stylus which was inspired from the force-field zone. If the distance between two styluses was closer than the diameter of the virtual sphere, it would be considered as the pen-points meet. Thus, the sender and receiver could easily handoff objects when the receiver's stylus moved inside of the sender stylus's sphere. Figure 39 shows the sequence of the 3D-handoff technique and the virtual sphere we applied for each stylus to help users easily handoff objects in 3D space.

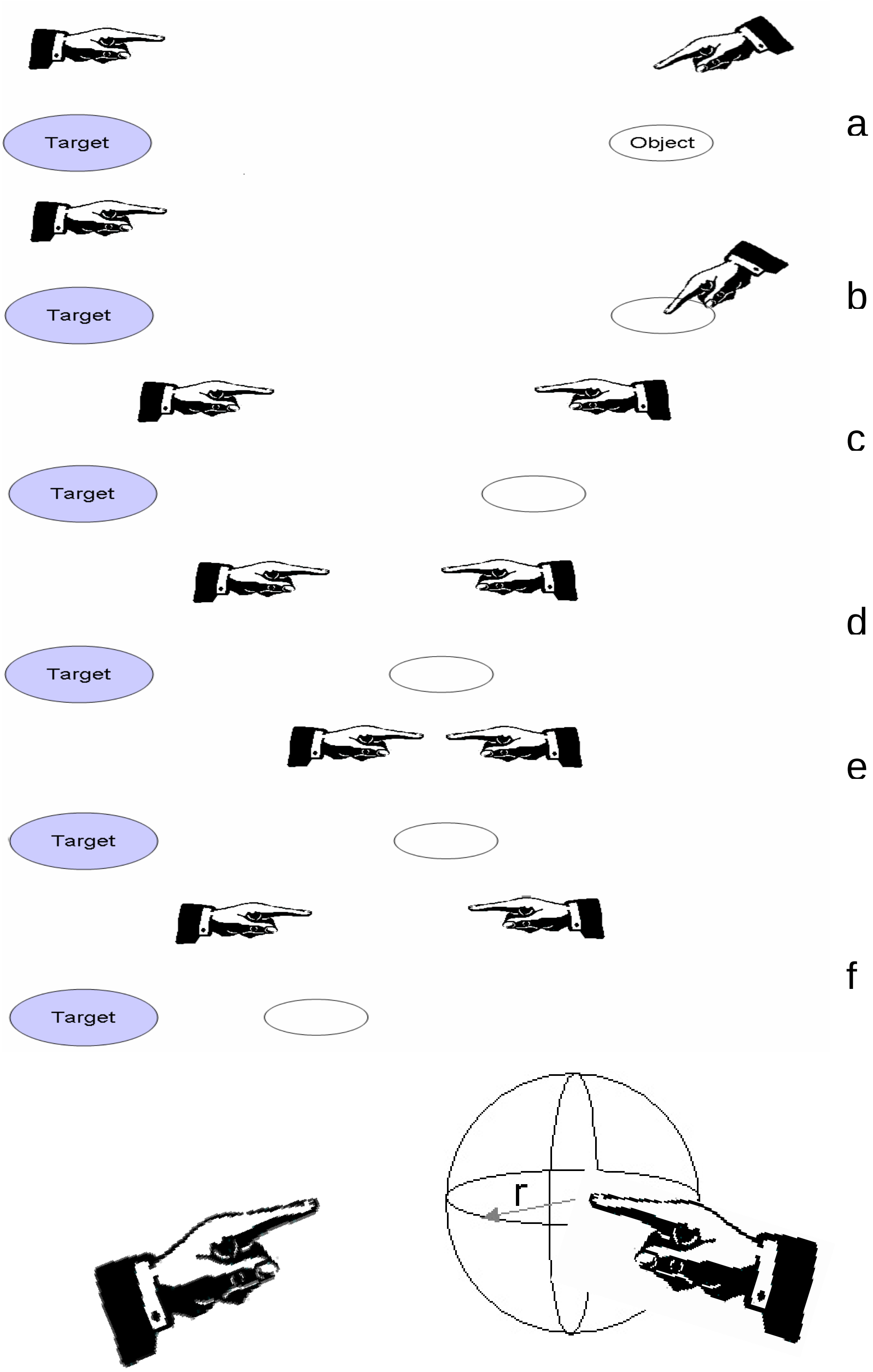


Figure 39: the sequence of 3D-handoff technique and the virtual sensitive 3D sphere around the stylus.

Digital jigsaw puzzle game

Environment and Apparatus

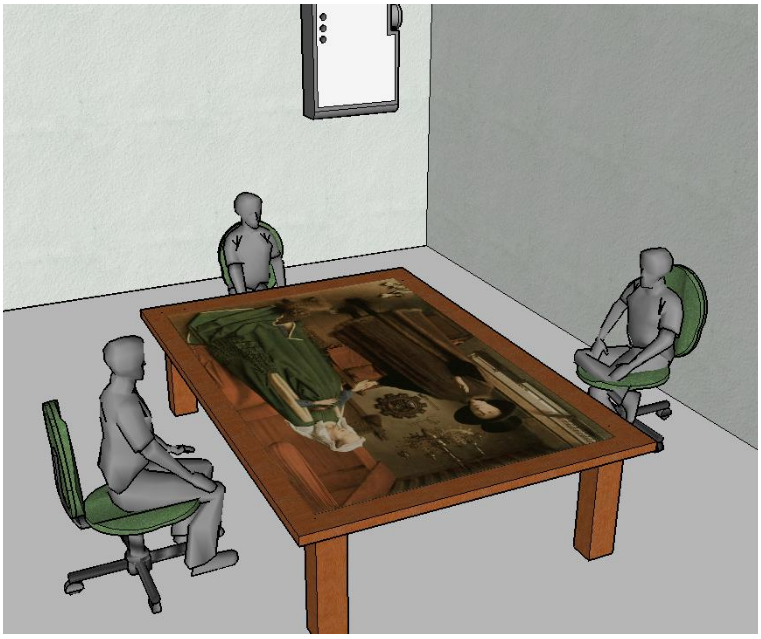


Figure 40: The digital jigsaw puzzle game environment.

Shown in figure 40, the digital tabletop system was a rectangle wooden table (62 inch * 49 inch). We used a top-down projector mounted on the ceiling to create a large horizontal work-surface which served as the display environment for the experiment. We used a 6DOF Polhemus motion tracking system with three styli for user input. Both the Polhemus and the projector were connected to a Dell 3.20 GHz Pc with 512 MB ram running Microsoft Windows XP. The motion tracker continuously updated the 3D position of each stylus. The experimental setup could only support three participants working together. One sat on the left side of the table edges, one on the top side and one on the right side. Each person was using one stylus to manipulate and transfer/handoff the puzzle pieces. These participants collaboratively played the digital jigsaw game together.

Task

Figure 41: the original picture for the digital jigsaw puzzle game. [5]

We chose the digital jigsaw puzzle game because it is similar with the real-world task examined in Chapter 3 and simple to implement. This would give us the opportunity to compare the usage of the transfer/handoff techniques between the digital tabletop and real world table.

We projected a picture (shown at figure 41, 1024 pixel * 768 pixel) on the tabletop. The picture's orientation was toward the user who sat at the top side of the tabletop, so it was comfortable for all of the three users to see. We separated the picture into 16 parts in height and 12 parts in width (One piece of puzzle was 3.2 inch * 3.2 inch) for a total of 192 pieces, and randomized the positions and orientations of these pieces. These puzzle pieces were randomly categorized into three piles and placed them in front of each participant. The task was designed so that normally 3 users could not finish within 60 minutes, so we had enough time to focus on the object transferring during the collaboration. To achieve the task, participants had to collaboratively move and rotate the puzzle pieces to reconstruct the original picture.

Design

We recruited 4 groups of people. All of them were right handed university students, age from 24 to 34 with various cultural backgrounds. There were three people for each group. Each group of users had 50 minutes to start from shuffled puzzle pieces and tried to solve the jigsaw puzzle as much as they could.

To rotate the puzzle pieces, the TNT [18] technique was deployed. When users spin the stylus, the selected puzzle piece would rotate the same amount of angle in the same direction. To select the puzzle pieces, user had to approach his stylus to the puzzle pieces. When the stylus touched the table surface where the puzzle piece was projected, the user could press the stylus button. Then the puzzle piece would follow the stylus' movement. To deselect the puzzle piece, user just released the stylus button. Then the puzzle would stop the movement.

To transfer an object, users had four possible techniques: deposit, traditional handoffs, force-field handoff and 3D-handoff. The size of the force-field zone was a circle around the stylus and the radius was the height of one puzzle piece (3.2 inch). And the radius of the virtual 3D sensitive sphere was the height of one puzzle piece as well. We chose the height of the puzzle piece to be the radius because we wanted the stylus cursor to be projected inside of the puzzle piece while the force-field or 3D virtual sphere was affected. So, both the sender and the receiver could be aware that they could still control the transferred object during the handoff.

We were focusing on how people use transfer techniques in real tasks. Users could freely choose and switch to the most appropriate transfer techniques for them. However, the traditional handoff techniques conflicted with the force-field handoff technique. In order to provide users as many opinions as possible, we separated the four transfer techniques into two categories.

Category 1. Deposit, traditional handoff, 3D-handoff

Category 2. Deposit, force-field handoff, 3D-handoff

The experiment used a within group design with a total time for the task of 50 minutes. Each group was given 10 minutes at the beginning to get familiar with the various techniques. They then did the task with each category of techniques for 20 minutes. To balance the order, two groups started with category 1 and then did category 2 while the other two groups started with category 2 and then went to category 1.

Measures

To better analyze the transfer activities and the context, we used two types of recording mechanism: log files and video tapes. For the log file, the computer recorded the time when a transfer action happened; and the name of the techniques as well. The name of the technique was only a sensible guess and it was corrected later by observing the video. It was regarded as deposit if the time between the sender dropping the object and the receiver picking the object up was longer than 0.5 second. It was counted as 2D-handoff if both the sender and receiver's hands were kept on the table surface during the handoff. And if input styluses were kept on the table surface during the handoff, it was also counted as 2D-handoff. All the other handoff actions were going to be counted as 3D-handoff.

We also used video tape to record the whole jigsaw puzzle game procedure. We analyzed the video afterwards to better understand the context and did some corrections for each handoff action. We did this because the sensor could not detect whether the users' hands were kept on the table surface during the handoff or not. So we had to use video tape to determine which handoff technique was used. Another reason was that we needed to analysis the video to find the possible reasons for some unexpected results or issues.

After the whole experiment, we asked the participants to fill out a post-questionnaire. This could help us get the data about the users' preference, effort of usage and frequency of usage.

Results

This was an observation based user study for using four transfer techniques on the digital tabletop system for real tasks. We were interested in which techniques were used, how participants use these techniques and their performance. We also analyzed the difference and similarity of using handoff and deposit techniques in a digital world and the real world.

Deposit and Handoff techniques

We found that object transferring was an important activity in digital puzzle game as well. On average users transferred 1.06 objects per minute. Participants frequently used both the deposit and the handoff techniques to accomplish the transfer. Figure 42 shows the usage number of handoff and deposit technique for each group and the last column indicates the overall usage number. On average users used handoff 54.72% (116 of 212) to transfer the object.

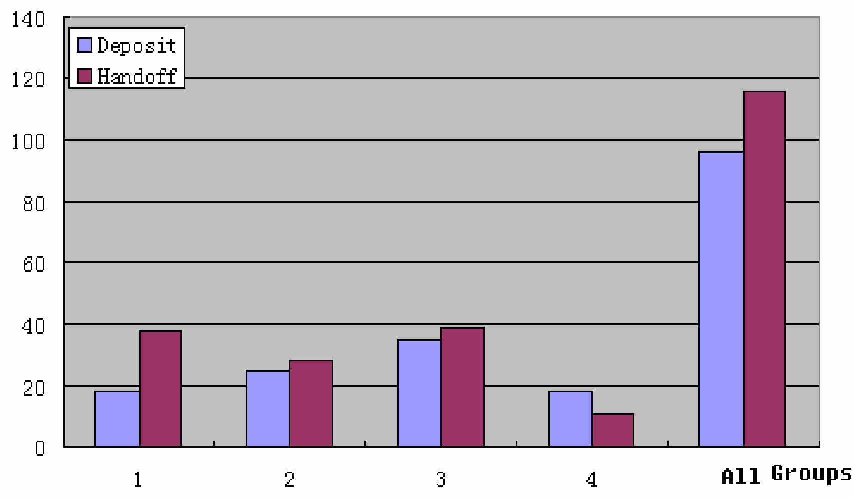


Figure 42: Number of handoff and deposits.

Traditional handoff and force-field handoff

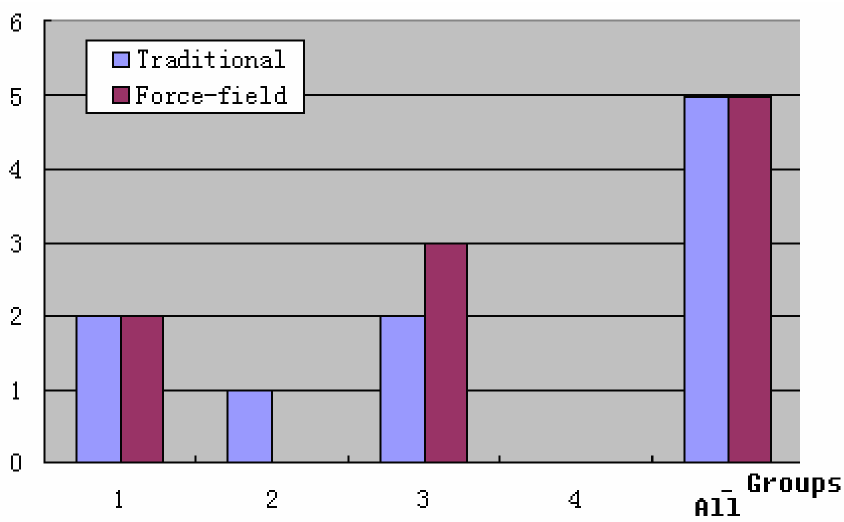


Figure 43: Number of traditional handoff and force-field handoff.

For two categories of the transfer techniques, it was surprising that participants only used very few times the traditional handoff and force-field handoff (figure 43) on the digital tabletop. We thought that it was probably because the 3D-handoff technique and the deposit technique were always available and these two techniques were preferred by users and they could perform better than the 2D-handoff techniques. Thus participants used the 2D-handoff techniques very few times, even though they were improved. It was a similar situation in the real world table tasks observation.

2D-handoff and 3D-handoff techniques

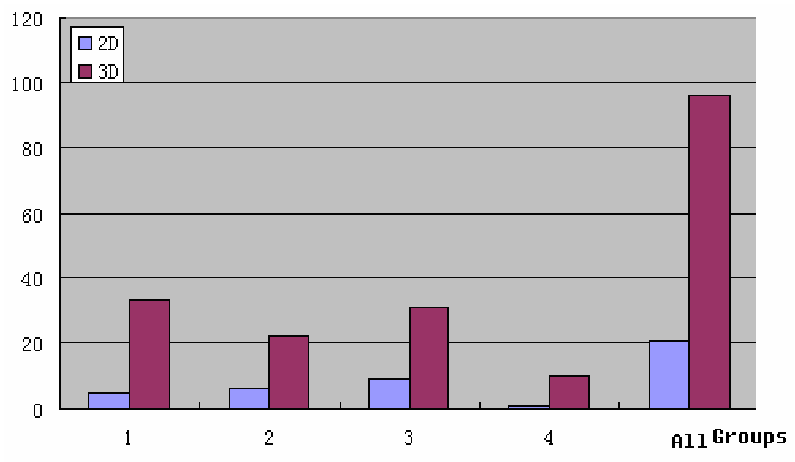


Figure 44: Number of 2D-handoff and 3D-handoff.

We also found that users typically employed both the 2D-handoff technique and 3D-handoff technique to handoff objects. On most occasions users exploited the 3D surface above the table to complete their handoff actions. Only in very few occasions did users restrict the movement of puzzle pieces to the surface of the table to perform a 2D-handoff. Figure 44 shows the number of 2D and 3D handoffs for the digital jigsaw puzzle game. On average users used the 3D-handoff technique 82.05% (96 of 117) to transfer the object.

Subjective data

After the task, each user was asked to rank four transfer techniques from 1 to 4 in frequency of usage, effort of usage and overall preference. For the frequency of usage, 1 meant most frequently used and 4 meant less frequently used; for the effort of usage, 1 meant need a lot of effort and 4 meant need little effort; for the overall preference, 1 meant the best technique and 4 meant the worst technique.

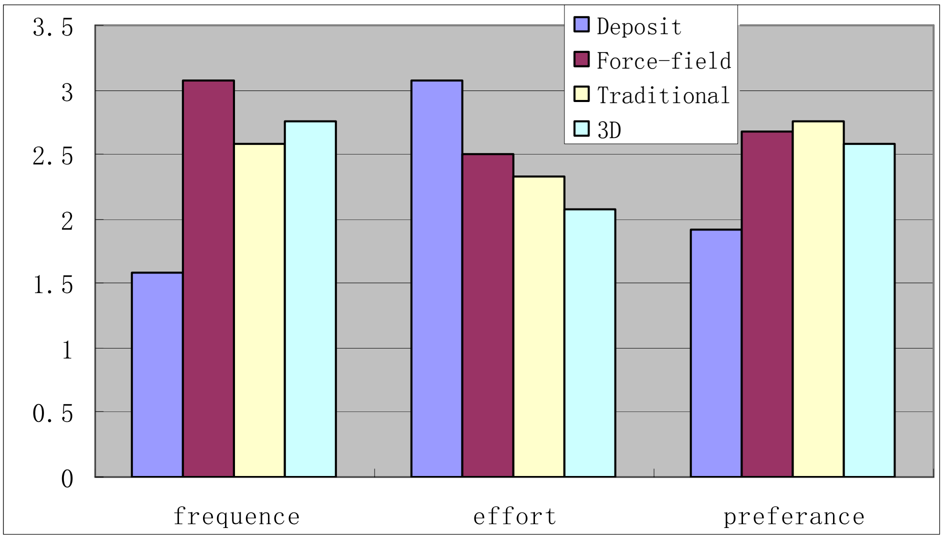


Figure 45: Average user preference scores for each interaction technique.

Frequency of usage:

Figure 45 shows that participants thought the deposit technique was more frequently used than the traditional handoff technique, the force-field technique and the 3D-handoff technique.

Effort of usage:

Figure 45 also shows that the deposit technique needed less effort than any other transfer techniques. Among the handoff techniques, the force-field technique needed less effort to use, followed by the traditional handoff technique, and then was the 3D-handoff technique.

Overall preference:

From figure 45 we can see that most of the users prefer using the deposit technique to transfer objects. However, the 3D-handoff technique was the most preferred among handoff techniques, followed by the force-field technique and the worst one was the traditional handoff technique.

Discussion

Here we discussed results of our digital Jigsaw game and compare our results with those of the real-world observation study.

Handoff and deposit

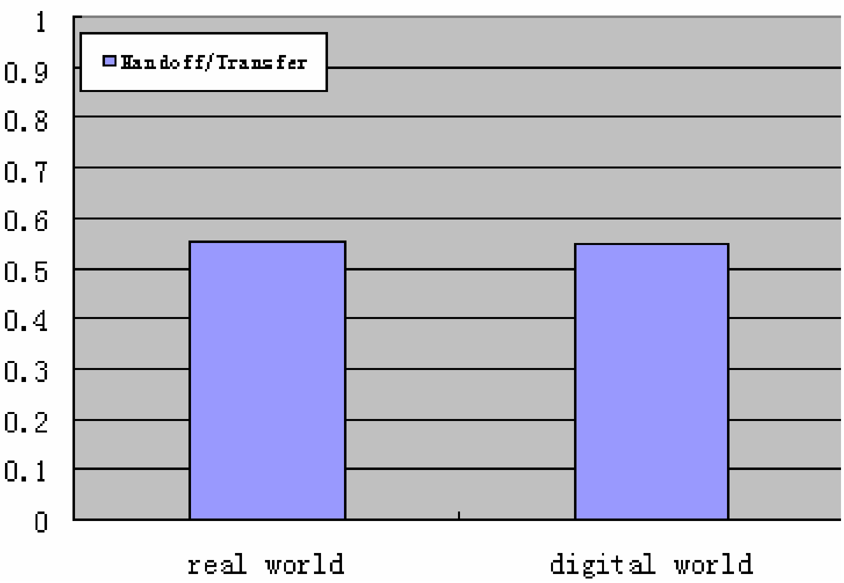


Figure 46: The percentage of handoff out of transfer in real world and digital tabletop system.

There were totally 116 handoff actions and 96 deposit actions in the digital tabletop system. The percentage of handoff was 54.72% of the total transfer. In comparison, task-3 of the real-world observation (chapter 3), there were a total of 51 handoff actions and 41 deposits. In the real-world tasks, handoff amounted to 55.43% of the total transfers. Figure 46 shows the ratio of handoff to total transfers in both real-world and digital-world for the jigsaw puzzle task. We believed that participants utilize handoff and deposit in a similar distribution in the digital and real-world tasks.

As reported in the results section, the deposit technique got better user feedback than all the three handoff techniques in frequency of usage, effort of usage and overall preference. One reason for this could be that the deposit technique needed less coordination and communication between users when compared to the handoff techniques. Even though participants felt that they used deposit more frequently than handoff, the analysis of log-files and video show a different picture. Since we did not collect such data from the real-world observation study, due to lack of current insight it was difficult to estimate if users generally expected to use deposit more often than handoff. This needs further investigation in future studies. It was also important to examine novel strategies to improve the users' coordination and communication during handoff both in 2D and 3D space, such as making the transferred object intelligent or predicting the users' purpose.

2D-handoff and 3D-handoff technique

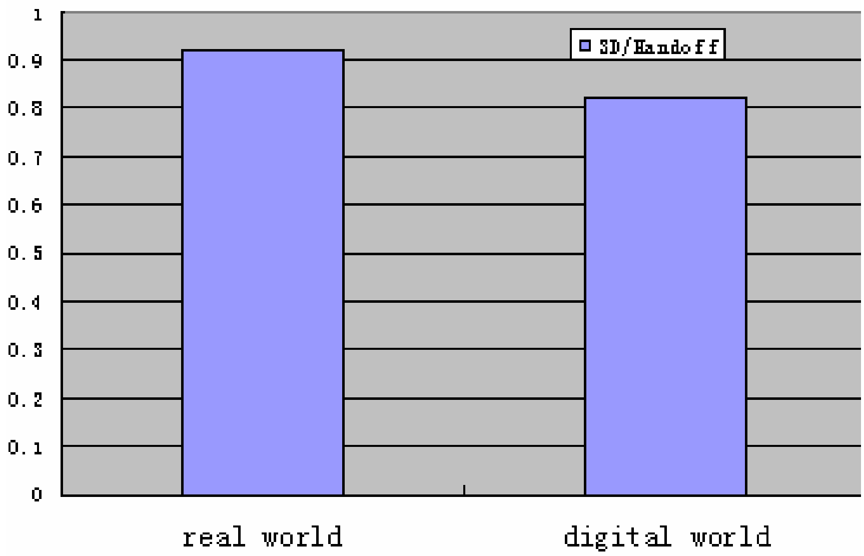


Figure 47: The percentage of 3D-handoff out of 2D-handoff in real world and digital tabletop system.

From figure 47 we can see that the percentage of 3D-handoff out of total handoff for digital tabletop system was 82.05% (96 out of 117), while the percentage of

3D-handoff out of total handoff for real world tabletop was 92.16% (47 out of 51). There could be several reasons for this difference. Due to the small sample size it was not possible to reliably perform any statistical test on this data. If we can have enough money and resources, we will recruit more participants for experiment and we think the result will be the same. However, it did suggest that users still had problems using the 3D-handoff technique in the digital tabletop system, meanwhile they found it fairly straight forward to use in the real world tabletop. The reason probably was that the digital tabletop system for our experiment used a top projected system. Even though the sender picked up the object and manipulated it in 3D space; the object was still projected on the table surface. This confused the receiver when he grasped the object from the sender: where should they move their stylus - to the sender’s stylus which was waited above the table surface or to the projected object which was on the table surface? Initially, the receiver would approach the projected puzzle piece, and found it did not work. Then both the sender and receiver adjusted their hands and styluses to finish the 3D-handoff for the digital tabletop system. However after a few minutes of training, the confusion could be solved. Figure 48 shows an example scenario that the sender’s stylus (emphasis in red) was above the table surface and waited for the receiver to pick up the selected puzzle piece (emphasized in blue). But the receiver’s stylus (emphasized in orange) went to the image of the selected puzzle on the table surface.

As reported in the results section, participants thought they used traditional handoff technique more often than 3D-handoff technique. But by subjects overall preference and by analyzing the log file, it was the opposite. We believed that 3D-handoff was so natural and intuitive that users were not conscious of their frequent use of the technique.

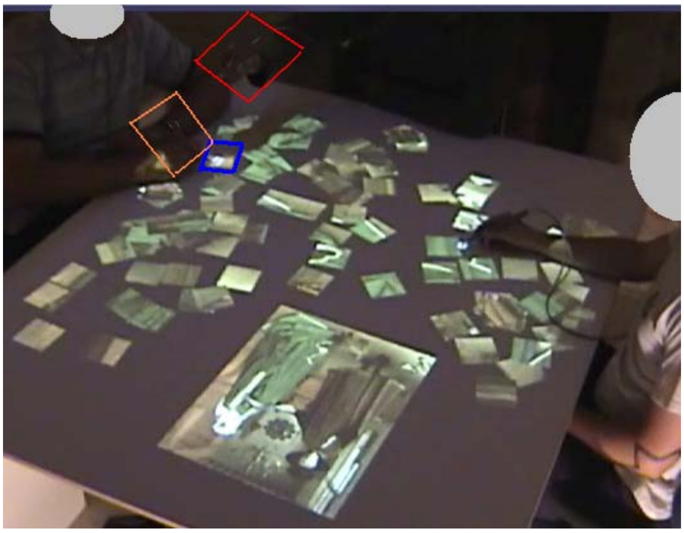


Figure 48: Confusion for the receiver while using 3D-handoff technique

3D-handoff and Interference

Figure 49: A user is manipulating puzzle pieces by 3D-handoff technique to avoid the interference with the others in the shared space.

Another interesting finding was that users like to use the stylus to select a piece of puzzle on the tabletop surface, and then moved the stylus way-above the tabletop surface to find a suitable position in the picture for the selected piece. When designing the 3D-handoff technique we did not anticipate this use, however users frequently chose to use it as a technique to avoid the interference with the others. Shown in figure 49, the user sitting on top side of the table (emphasis in red pen) selected a piece of puzzle and rotated it in the shared space between the two users. Here he was seen using the technique to manipulate the puzzle piece above the table surface to avoid interference with the other person (emphasis in orange pen).

Summary

By observing 4 groups of subjects doing a jigsaw puzzle game on digital tabletop system, the results showed that on the digital tabletop system the usage percentage of deposit, 2D-handoff and 3D-handoff techniques was similar to these techniques on the real-world table. The 3D-handoff technique was intuitive and preferred by users. And compared with other handoff techniques, 3D-handoff technique could cause less interference problems. The force-field technique was more preferred by users than traditional handoff technique, which proved our experiment results in the chapter 4.

Because the display system was top projected, it could not fully present the 3D environment especially when people used the 3D-handoff technique to handoff objects. It confused users a little at the start. However, after several trials of training, the problem could be solved.

CHAPTER 6
DISCUSSION, CONCLUSION AND FUTURE WORK

We observed how people transfer and handoff objects on a real world table, and conducted a series of user studies to evaluate and improve the handoff techniques in the digital tabletop systems. In the previous chapter we discussed the findings from our experiment; here we discuss some general points for designing handoff techniques on the digital tabletop system.

Discussion

Hardware for Digital Tabletop System

Advanced hardware is important for digital tabletop design, which determines the users' input devices and actions for the virtual artifacts on the tabletop. The novel sensing technology and display system can support users to handoff objects much more easily.

Sensor

In our user studies, we use stylus sensors of Polhemus Liberty, which provide 6 degree of freedom (DOF) data. These sensors let us easily get and calibrate the precise positions in the 3D space, and then project them on the tabletop. Since styli were the only input devices for our digital tabletop system, we can not completely simulate the real world table environment which has many input devices, such as multiple point input devices, complex hand gestures, and even users' emotion detectors. For example, we believe that with some emotion sensors, users can easily understand what the other people are trying to do. Thus, the sender and receiver can have better coordination to help the handoff action. The tabletop system should allow users to choose multiple input devices for their tasks, such as touch sensitive table surfaces which allow users to directly interact with their fingers or palms, or digital gloves which let users grasp the virtual objects. And users should also fluently switch among these input devices when they are facing different tasks and requirements. The users can perform handoff actions better on the digital tabletop system; and gain more satisfaction.

Virtual 3D display

As we pointed out in chapter 5, top projected or bottom-up projected display system constraints the digital object to be displayed on the 2D tabletop surface. It can not fully represent the 3D spatial environment on and above the digital tabletop surface; especially when users interact with the digital tabletop or the other people with 3D actions. The limitation of the display system confuses the users and makes them not aware of the situation on the digital tabletop and the other collaborators. The issue would be changed, if we use virtual environment helmets or even more advanced display (support 3D) for users and digital tabletop systems. Then, the users can perform naturally, interact initiatively and easily comprehend with the digital artifacts and their situations on the digital tabletop system.

Tactile feedback from tangible handoff

With tactile feedback, users should not only rely on their vision to do the interaction, they also want to touch and feel the physical representatives for the virtual digital objects, which provides more information and can help users to interact with digital objects. There are two ways to help users to handoff objects with tactile feedback on the digital tabletop system. One is to use tangible objects to represent the digital object. We can provide several physical blocks; users can achieve handoff of digital objects by handing-off these blocks on the tabletop system. However, because the number of the physical blocks is limited, the tangible block handoff technique is not suitable for handing-off or transferring a large amount of digital objects. Another way is to add tactile feedback to the input devices. If we could apply tactile feedback to the stylus used in our user studies, users can feel whether the force-field or 3D virtual sphere is affected, whether the receiver picks up the transferred object and whether the sender releases the object, etc. With the help of these feedbacks, it broadens the interaction bandwidth. Users can feel the stage of handoff and the situation on the digital tabletop system.

Software of Digital Tabletop Systems

A robust software system is important for digital tabletop systems. It can make the digital objects appear as good as physical ones and alleviate users' workload to easily share and handoff objects.

Transfer Negotiation

As we discussed in chapters 4 and 5, negotiation between the sender and receiver is the bottleneck for handoff techniques. Although the force-field technique improves the negotiation mechanism, it is still not good enough. For example, the time for one person transferring an object from his left hand to right hand is much shorter than the time for two persons handing-off objects between each other. It is because one person can coordinate his left and right hands very well to achieve the handoff task. But for two people, they have to communicate to coordinate their collaborations. After the experiment, some participants told me that they have to predict whether and what the others want to transfer or handoff. Then he starts to adjust his own action to coordinate with that person. Comparing with the real world traditional table, the digital tabletop system should become smarter. The tabletop should be intelligent enough to predict each user's action, notify the other people who will be involved in the handoff action and enhance users' collaboration awareness. The software of digital tabletop system should be a bridge between the sender and receiver's brains, coordinate two peoples' hands to achieve handoff action as good as one person's left and right hands.

Size of the force-field zone and the 3D virtual sensitive sphere

In Chapter 4 and 5, in order to help the receiver better retrieve the object from the sender, we invented the force-field zone and 3D virtual sphere respectively, which make the 2D and 3D-handoff techniques easier. The size of the force zone and 3D virtual sphere is important. Although we are very careful about the diameter of the force-field zone and 3D virtual sphere, we still find that interference happens when a user wants to select a piece of puzzle near another user's current selection. In our user studies and tasks, the radius of the force-field zone and 3D virtual sphere is fixed. However, the software should be smart enough to deal with the interference based on users' intension and the environment. For example, we can use Grossman's Bubble

Cursor [6] to automatically expand or shirk the size of the force-field zone or 3D sphere to avoid the interference.

The distribution of the force-field and 3D sphere is equally distributed around the stylus. The handoff techniques can perform better if the distribution changes dynamically based on the situation on the tabletop and the context of current user's stylus.

Conclusion

We had held an observational study and several user studies to investigate and improve the handoff techniques on the digital tabletop systems. It includes:

An observational study was held to study user handoff actions in the real world traditional tabletop. And from the observation, we categorized handoff actions into 2D-handoff and 3D-handoff; identified three user roles and the procedure of the handoff action on the tabletop; and summarized several guidelines for designers to support handoff action on digital tabletop systems. Then we ran a pilot study to compare the traditional 2D-handoff with tangible handoff techniques, and found that traditional 2D-handoff technique was slow and was not preferred by most of the participants. The problem for traditional 2D-handoff technique was that the sender and the receiver needed more time to negotiate and coordinate with each other during the handoff. Then we improved the traditional 2D-handoff technique by applying a force-field zone. And the evaluation showed that force-field handoff techniques performed better than traditional 2D-handoff techniques, and it was equivalent to the tangible media block handoff technique.

Because we found that people prefer to use 3D-handoff to handoff object in the real world tabletop tasks. We implemented an equivalent 3D-handoff technique for digital tabletop system. We used a virtual 3D sensitive sphere to help users use 3D-handoff technique to transfer object. Finally, we examined four possible transfer techniques (including deposit, traditional 2D-handoff technique, force-field 2D-handoff technique and 3D-handoff technique) in a jigsaw puzzle game on the digital tabletop. And we found that with these techniques, the percentage of participants' handoff action and transfer action in the digital tabletop was similar with the real world tabletop.

The outcomes of this research can be easily directly applied to any current digital tabletop system. With the help of handoff techniques in this thesis, users can naturally and quickly perform handoff action in the digital world. They can feel these handoff techniques are similar to what they used in the real world. The guidelines concluded from observation study also can help the other researchers or designers when they carry on future study in related areas.

Future Studies

For the future studies, we have already mentioned several points in the discussion section of chapter 6. They are about how to improve the digital handoff techniques with the advantaged hardware and software; so the digital tabletop system will become smarter and users can freely interact with it.

Another possible future work will be handing-off objects with different input devices. As we discussed previous, we only provided styluses as input device in our experiment. However, in the real situation, people may come to a digital tabletop system and interact with other people casually with different input devices. Every input device has its own advantages and disadvantages, and every user has its own habits to use a certain input device. Users will interact with the digital tabletop and transfer/handoff objects between each other differently with different input devices. With these new situations and differences, users will change their handoff habit to adapt to the new environment. Thus, new handoff techniques and new negotiation mechanisms are needed to help users' handoff objects on the digital tabletop systems.

All the previous future studies for handoff techniques talk about the handoff objects in co-located digital tabletop system environment. In the digital world, remote collaboration is another hot area and the remote handoff technique does not have the similar situation in the real world. There have already been several digital tabletop systems and techniques which support multiple users/groups to collaborate remotely. It is reasonable to expect that users need remote handoff techniques to handoff objects remotely. Remote handoff techniques are different from the co-located handoff techniques, because both the sender and the receiver are located at different places. It is difficult for users to communicate, coordinate and negotiate with each other, thus it is hard to predict whether, when and what the other people are going to handoff the objects. Since there is no physical embodiment for the remote collaborators, it is also impossible to use tangible media blocks to represent the transferred object to help users' handoff. These differences and problems for remote collaboration will change the users' action to transfer and handoff the objects.

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APPENDIX A
POLHEMUS LIBERTY SPECIFICATIONS

Update Rate	240 Hz per sensor, simultaneous samples
Latency	3.5 milliseconds
Number of Sensors	240/8 has 1 to 8 sensors, 240/16 has 1 to 16
I/O Ports	USB; RS232 to 115,200 Baud rate, both standard
Static Accuracy	0.03 in. RMS for X, Y or Z position; 0.15° RMS for sensor orientation
Resolution	0.00015 in. (0.038 mm) at 12 in. (30 cm) range; 0.0012° orientation
Range	36 in. (90 cm) at above specifications; useful operation in excess of 72 in. (180 cm)
Multiple Systems	Provision available to operate two separate systems in same environment
Angular Coverage	All-attitude
Data format	Operator selectable ASCII or IEEE 754 binary; English/Metric Units
External Event Marker	User input flag and output marker
Output Sync Pulse	TTL frame sync output
Physical Characteristics	SEU w/power supply: 12.2 in. (31 cm) L x 7 in. (17.8 cm) W x 8.5 in. (21.6 cm) H; weight 9 lbs. (4.1 kg) 240/12 and 240/16: 12.2 in. (31 cm) L x 7 in. (17.8 cm) W x 11 in. (27.94 cm) H; weight 11 lbs. (5 kg) Field Source:

	Standard TX2: 2.3 in. (5.8 cm) L x 2.2 in. (5.6 cm) W x 2.2 in. (5.6 cm) H; weight 8.8 oz. (250 gm) TX4: 4.07 in. (10.4cm) L x 4.07 in. (10.4cm) W x 4.04 in. (10.3cm) H 1.60 lbs. (726gm) Long Ranger: Source is 18 inches in diameter Sensor: 0.9 in. (22.9 mm) L x 1.1 in. (27.9 mm) W x 0.6 in. (15.2 mm) H; weight 0.8 oz. (23 gm)
Power Requirements	85-264 VAC, 47 – 440 Hz, single phase, 50 W
Regulatory	FCC Part 15, class A CE: EN50081-1, class A, emissions EN50082-1, class 2, immunity EN61010, safety