Direct Intentions: The Effects of Input Devices on Collaboration around a Tabletop Display

Tara Whalen[†], Vicki Ha[†], Kori M. Inkpen[†], Regan L. Mandryk[‡], Stacey D. Scott[‡‡], Mark H. Hancock[‡‡]

[†]Faculty of Computer Science, Dalhousie University
Halifax, NS B3H 1W5
{whalen, vha, inkpen}@cs.dal.ca

[‡]Department of Computing Science, Simon Fraser University
Burnaby, BC V5A 1S6
rlmandry@cs.dal.ca

[‡‡]Department of Computer Science, University of Calgary
Calgary, AB T2N 1N4
{sdscott, msh}@cpsc.ucalgary.ca

ABSTRACT

This paper explores users' interpersonal interactions during collaboration around a tabletop display, in order to better understand the affordances offered by this medium. We investigate participants' collaborative interactions, particularly related to the type of input device provided. Stylus, mouse, and touch-based interactions were provided to allow multiple people to simultaneously interact with tabletop systems in a series of studies, and we observed how the choice of direct or indirect input device affected collaboration. In this paper we discuss how direct and indirect input affect gestures, natural interactions, ergonomics, territoriality, and awareness of both intention and action. The findings from our studies are presented, along with the advantages, drawbacks, and special considerations of each input type in the context of a tabletop setting. These results are valuable for those who deploy and design tabletop systems, by providing them with guidelines for appropriate choice of input device.

AUTHOR KEYWORDS

CSCW, tabletop displays, input and interaction techniques, user studies, collaboration, awareness

ACM CLASSIFICATION KEYWORDS

H.5.2. User Interfaces: Input devices and strategies; H.5.3 Group and Organization Interfaces: Collaborative computing

INTRODUCTION

Tabletop displays have been explored by many researchers (see Scott et al. [14] for a comprehensive overview). Within the area of tabletop collaboration, one area that has not been examined is how the choice of input device affects interaction between group members. From a non-technological perspective, a table provides an excellent environment to support group interactions and is often an integral piece of furniture used for co-located, cooperative work. In general, large, horizontal surfaces afford different kinds of interactions and uses than desktop computers. At the heart of these differences is the way people interact with the technology and with each other.

Although researchers have demonstrated many potential uses for tabletop displays, we are just beginning to understand how people interact with them and how to best design interfaces that maximize their potential [14, 8]. However, in order to explore new collaborative tabletop interfaces, researchers must first build a suitable tabletop display system. This involves making decisions about appropriate input and output devices for the tabletop [14].

Little is actually known about the benefits or drawbacks of common input devices, such as mice or styli, when used with tabletop displays. What effect do direct and indirect input devices have on collaborative interactions? What are the tradeoffs between choosing one input device over another? This paper addresses these questions through an investigation of the natural behaviour of collaborators sharing a tabletop workspace while using different input devices in a variety of conditions.

We first present related research on supporting co-located collaboration and tabletop display systems. We then describe our studies and the results obtained. In particular, we discuss our observations on how direct and indirect input devices affect gesturing, natural interactions, ergonomics, territoriality and awareness of intention and action. We also present a summary of the pros, cons, and considerations that must be taken into account when developing a tabletop system for collaborative use. Finally, we present some directions for future work.

RELATED WORK

Weiser's vision of ubiquitous computing included the notion that technology should be designed to fit into our natural human environment [22]. Thus, we should not force people to collaborate using technology that has been designed for use by individuals. Providing natural interfaces that facilitate rich interpersonal communication between humans has been proposed as an important research direction [1]. In particular, interfaces should support and utilize the way humans naturally interact with the physical world.

TABLETOP SYSTEMS

Desks and tables are used extensively to work with physical artifacts such as paper, books, and pens. However, more and more of our work is conducted using desktop computers. Previous literature suggests that tabletop display systems can bridge the physical and digital environments. A wide array of tabletop systems have been proposed, developed, and evaluated; see Scott et al.[14] for a detailed review of these systems.

Researchers are exploring the potential of tabletop displays to support collaboration. The InteracTable [17] and Stanford's Interactive Table [5] were designed to support cooperative work of dynamic teams. Tabletop systems have also been developed for teaching collaborative problem-solving, for example the EDC [3] and the Carletta [18] systems. The Personal Digital Historian [15] and the Pond system [16] are collaborative tabletop systems designed to allow small groups to browse and share digital information such as photos, documents, and music.

Tabletop displays have been used with a variety of input techniques. Wellner's Digital Desk [23] system used a vision based-system to track the user's finger and enable pointing at objects in the system. The Urp [21] system uses vision to track physical objects. The InteracTable [17], Personal Digital Historian [15], Responsive Workbench [7] and the Pond [16] use touch-sensitive displays, enabling people to write or draw on the table with a pen and interact via finger or pen gestures. The metaDesk [20], EDC [3], Carletta [18], SenseTable [10], and BUILD-IT [11] use tangible objects to interact with digital information. Other tabletop installations utilize traditional desktop input devices such as mice [9] and trackballs [7].

Two main reasons for the wide disparity in choice of input devices are the variety of tasks that can be performed using a tabletop display, and the inherent strengths and weaknesses of the input devices. In addition, there is a lack of understanding concerning users' interactions with the tabletop display and various input strategies. This clouds the decision as to which input device would be most appropriate.

RESEARCH STUDIES

We have performed a large number of studies on co-located collaboration, including studies in tabletop environments. Through our experience, we have observed a number of common behaviors that collaborators exhibit when using tabletops. Here we focus on three specific studies that shed light on how input devices affect collaboration. We describe these studies briefly, after which we present our main results, which provide insight into how best to choose an appropriate input technique for tabletop settings.

In order to support collaboration, it is important to consider interpersonal communication when choosing which input device to use. To address this issue, we completed a series of user studies, focusing on how direct and indirect input methods affect face-to-face collaboration around a tabletop display

STUDY ONE: INPUT DEVICES AND COLLABORATION

The first experiment was chiefly exploratory, with two main objectives: to gain general insights into users' interpersonal interactions when they collaborate around a tabletop display, and to investigate how different input device parameters impact these interactions. To investigate these goals, we observed users performing a collaborative card-matching game on a tabletop display. Participants used both mice and styli to interact with the tabletop. Our analysis focused mainly on non-verbal communication.

The "Memory Game" was a collaborative game developed for use in this study. The game involved twenty face-down playing cards, which contained ten matching pairs. Players searched for matches by turning over cards; only two cards could be face-up at a time. If the cards matched, the two cards disappeared. If the cards didn't match, they were turned face down again after a brief pause. Figure 1 shows a screenshot of the memory game.

Each time a card was turned over, one point was recorded.

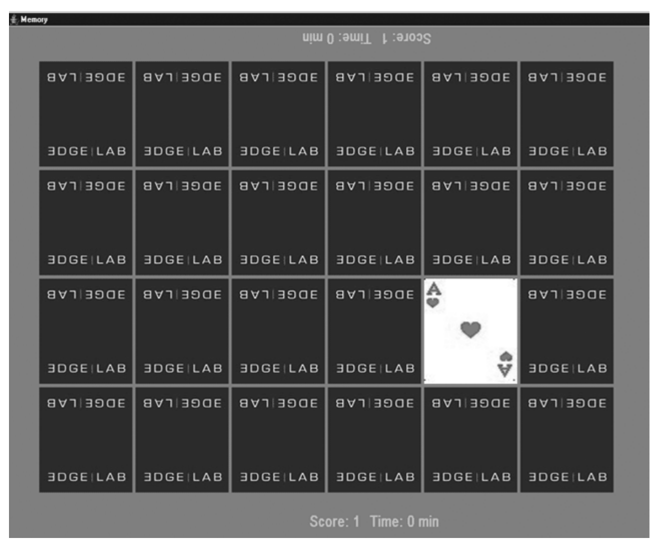

Figure 1:Screenshot of Memory Game software. Cards are turned over two at a time and removed if match is found.

The goal of the game was to find all of the matches while minimizing the total number of points. Both users were able to turn over cards at any time. This allowed the pairs to develop their own strategy for playing the game.

A pair of styli and a pair of mice were used for input. Participants interacted with a top-projected tabletop display consisting of a white laminate surface onto which output from a computer was projected (see Figure 1). Polhemus Fastrak receivers were used for the styli conditions. The styli were tracked in 3D space; moving the pen tip within 0.01cm of the table registered as a selection. For the two-mouse condition, we used the MID toolkit [6] to capture events from both mice independently.

EXPERIMENTAL DESIGN

12 pairs of university students (12 male and 12 female) participated in our study.

Each pair completed three repetitions of the memory game, once in each of the following conditions: shared mouse, shared stylus, two mice, and two styli. Each pair played 12 games in total. The order of the conditions was counterbalanced across the experiment to minimize learning effects. Participants were given the opportunity to practice the game once before the trials began.

Data for this study was collected through a background questionnaire, two post-condition questionnaires, and a post-session questionnaire, as well as videotaping, computer logging, and field notes.

STUDY TWO: AWARENESS OF INTENTION

We designed further tabletop experiments based on the results of Study One, which suggested that the use of the stylus helped to promote awareness of intention and action. That is, use of a direct input device allowed partners to more easily perceive what actions the other was taking or was about to take. We decided to further investigate awareness of intention and action in another set of experiments. In the first Memory Game study, we observed that when using two mice, participants encountered "collisions"—both people clicking on the same card unnecessarily. Therefore we decided to run the Memory Game again (with minor variations), to validate this observation. For this second study, we collected the number of collisions for both the mice and styli conditions in our log files. We hypothesized that there would be fewer collisions when the partners were using styli, which would indicate greater awareness of intention.

In this version of the Memory Game no score was recorded: instead, players were simply encouraged to finish the game was quickly as possible. We thought this approach would motivate users to maintain awareness of their partner's intended actions, in order to avoid the inefficiencies of collisions.

EXPERIMENTAL DESIGN

12 pairs of university students (19 male, 5 female) participated in our study.

Each pair played a practice game, followed by 10 trials (with a short break halfway). They did this for each of two conditions: mice and styli, with 20 recorded games in total. This was a within-subjects design and was counterbalanced so that half of the pairs started with mice and half with styli.

Data for this study was collected through a background questionnaire, two post-condition questionnaires, and a post-session questionnaire, as well as videotaping, computer logging, and field notes.

STUDY THREE: AWARENESS OF ACTIONS

We also explored how input devices affected awareness of actions carried out on the tabletop. Within this study, we measured the time taken to respond to a partner's actions. The task we designed was a search game: a pair of users competed to find images within a large set. The pair were given the same set of images to find. Each person individually clicked on the target image when they found it. We expected that players would "copy" the move after their partner found a card, so having greater awareness of actions would make the overall search time quicker. (We would expect the intervals between Player A's discovery and Player B's discovery to be shorter when awareness is strong.) Using a DiamondTouch touch-sensitive tabletop display, we ran a series of games with two conditions: mice and touch-based input. We hypothesized that the intervals between discoveries would be shorter with touch-based input than with mice.

We developed the "Search Game" for this study. Users were each given the same set of five images, and had to find all five images, in order, within a larger set in the middle of the display. (The images varied in color as well as design, and were symmetric across the horizontal axis). Once a user found an image, he would select it; if he

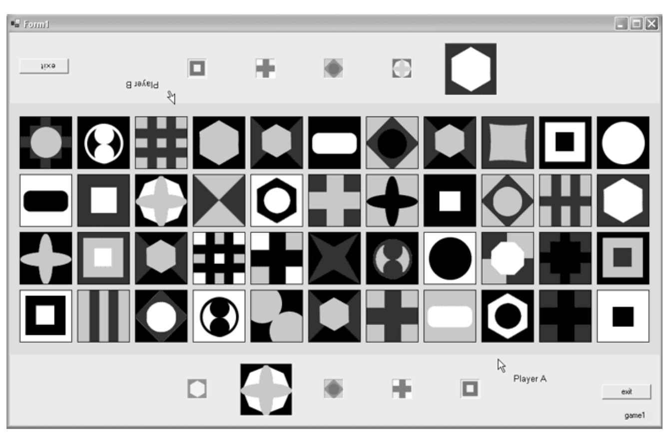

Figure 2: Screenshot of Search Game application. The large icons in the top-most and bottom-most rows are the ones that the users are currently looking for.

correctly located it, he could then move to the next item. A screenshot of this application is shown in Figure 2.

The object of the activity was to find all five items faster than your partner, so the game involved no collaboration—only competition.

For the Search Game, two USB mice, along with a DiamondTouch serial tabletop display [6], were used. The display was top-projected onto the surface of the DiamondTouch, a multi-user, multi-touch tabletop surface. Users could select an item by just touching it with their finger.

EXPERIMENTAL DESIGN

24 university students and staff (18 male, 6 female) participated in this study. Participants were placed into pairs for the study.

Participants played a practice game, followed by 10 recorded games (with a short break halfway). They did this for two conditions: mice and touch, for 20 recorded games in total. This was a within-subjects design and it was counterbalanced so that half of the pairs started with mice and half with touch.

Data was collected through a background questionnaire, two post-condition questionnaires, and a post-session questionnaire, as well as videotaping, computer logging, and field notes.

RESULTS AND DISCUSSION

Across all three studies, we found no significant difference in performance across the different input device conditions. However, we did notice several behavioral differences in these studies. In particular, these results relate to five aspects of collaboration and tabletop use: natural interactions, ergonomics, gesturing, territoriality, and awareness of intention and action.

GESTURING

Our first experiment focused heavily on non-verbal communication: in particular, we investigated gestures, using video analysis. A gesture was defined as a motion with the hand or input device, used to communicate information about a specific artifact in the Memory Game. We analyzed both physical and virtual gestures, as described below.

FIRST STUDY

PHYSICAL GESTURING

Physical gestures included all recorded gestures with the exception of those made with the mouse cursor. Participants exhibited a large number of physical gestures throughout the sessions. When using styli, participants often used the stylus itself as a gesturing tool. Hand gestures were made using both the hand holding the stylus as well as the other hand. When using a mouse, participants' physical gestures were primarily with the hand not holding the mouse, as they rarely removed their hand from the mouse.

The average number of physical gestures observed per session for each condition was 15 for the mouse, and 55 for the styli. Participants exhibited significantly more physical gestures when using the stylus than when using the mouse ($F_{1,11}$=25.88, p=.000, η^2=.702).

VIRTUAL GESTURING

Video data were also used to determine the number of virtual mouse gestures participants made. In lieu of gesturing with their mouse hand, participants frequently used the mouse cursor to make virtual gestures towards artifacts in the application. The average number of cursor gestures per session for both participants was 30. This was less than the amount of physical gesturing with the stylus—41—although this difference was not statistically significant ($F_{1,11}$=1.90, p=.195, η^2=.147).

Although virtual gesturing with the mouse cursor was common, it was problematic given the increased cognitive load involved in following a cursor on a large display surface. Several participants commented on this problem in the post-session questionnaire, particularly with multiple cursors on the screen. They claimed that it was difficult to keep track of the mouse cursors, that it was difficult to distinguish between multiple cursors, and that the presence of multiple cursors was distracting. These difficulties may have contributed to a decreased awareness of the intentions and actions of their partners. This observation was substantiated by the frequency of conflicting interactions when players would simultaneously act without an awareness of actions that their partner was making in parallel.

SECOND STUDY

For this study we did not explicitly record gesture information, although we asked about this in the post-session questionnaire. When asked, "Did you feel you gestured more with the mouse or the stylus?", 21 out of 24 participants selected "stylus." One participant commented, "Since I was moving my hand around with the stylus anyway it was natural to gesture, but with the mouse, gesturing would mean using my left hand or releasing the mouse." These results are consistent with our earlier findings. (No gesture data were gathered from the Search Game, as this was not applicable to a competitive game.)

NATURAL INTERACTIONS

One of the most compelling results of all three studies was how naturally the participants interacted with each other and the table. Many of their gestures and interactions on the tabletop display system were akin to those exhibited when sitting around a table. Pointing was utilized by every participant. They pointed and touched the virtual artifacts on the table in the same manner as if they were physical objects, often using both hands.

Leaning on the table was also a common occurrence. Just as people would when interacting around a traditional table, participants instinctively leaned in and rested their arms on the table as they engaged in the activity, especially when using styli. In the first two studies, as cards were cleared from the table, the participants intuitively treated the black background as physical table space, and often utilized it by leaning further into the table or resting their arms on it.

The stylus promoted natural interactions around the tabletop display. Participants in the first Memory Game study rated the stylus as being more natural and easier to use than a mouse when working on a tabletop. This was also evident in their behaviour. When participants were using mice they did not appear to be physically engaged with the table. They tended to lean back or sit motionless, primarily interacting through the mouse. Conversely, when using styli, the participants were considerably more dynamic. Their increased physical activity included reaching, pointing, and leaning. One participant commented on this aspect in the post-session questionnaire: "the stylus was easier than the mouse, more direct, you point and click rather than move your wrist in small motions to put a cursor in the correct place". Note, however, that this increased physical activity may be distracting, as it draws attention away from the display. In addition, physical movements over the tabletop may obscure portions of the display.

Many participants felt that the stylus was an intuitive input device for a tabletop system. Comments included: "[the] stylus is a lot easier to use and is much more natural"; "I could point out my selections better with a stylus"; and "[the] stylus did feel more natural due to its pen-like design". Participants were also comfortable using a mouse on the tabletop display and many expressed familiarity as its primary benefit. However, using a mouse had other drawbacks. Because of the constraints when using a mouse, some participants actually sat in an awkward position rather than taking the necessary time to configure their physical setup.

In the first Memory Game study, some participants suggested that using a touch sensitive display might be more appropriate. A touch sensitive display is an obvious choice for a tabletop display system. Intuitively, when people first approach a tabletop system, the first thing they want to do is touch it to interact with it. Our participants enjoyed interacting with the touch-sensitive display used for the Search Game: when asked whether they preferred touch-based or mouse-based input; 15 out of 24 preferred the touch-based input. Their comments included: "User friendly and…natural response"; "It is more instant, more direct"; and "Well, it was fun."

However, the benefits of a touch sensitive display must be balanced against the disadvantages, such as unintentional interactions. For example, tables in the physical world are used as placeholders for objects. Items like coffee cups, papers, pens, etc. are often placed on a table while working. We do not want our table to unintentionally react to the touch of these objects. Additionally, since users frequently leaned on the tabletop, it was important to not interpret this contact as an interaction with the system.

In the first Memory Game study, one participant commented that it was "nice to be able to point with your finger and not activate anything". (Many participants rested their fingers on artifacts, with no intention of selecting them.) Note that stylus users in both Memory Game studies inadvertently selected cards when they were gesturing (with the stylus) close to a card. While it can be helpful to have a sensitive input device, this ease of selection is a double-edged sword.

ERGONOMIC ISSUES

The choice of input device has a substantial effect on the ergonomics of a tabletop system. Direct input devices have some major drawbacks in terms of physical interaction with the tabletop display. Both the stylus and touch-based interaction techniques in our studies were reported by many participants as being tiring. In the second Memory Game experiment, 14 out of 24 participants preferred using the mouse over the stylus; of these 14, nine cited ergonomic reasons for their choice, stating that the mouse was less tiring, required less effort, and/or made it easier to reach objects on the far side of the table.

The second Memory Game experiment was run on a relatively large tabletop display (150cmx107cm). In contrast, the Search Game experiment was run on a much smaller touch-sensitive display (90cmx60cm). For the smaller display, most participants (15/24) preferred the direct input device, even though they were required to reach objects on the far side of the table. Of the nine who preferred the mouse, four cited ergonomic reasons—predominantly that using their arm was tiring. This effect was not so dominant as in the larger table, even though participants were required to reach objects on the far side of the table. However, it is still important to note that even with a small tabletop, some users may find direct input uncomfortable.

Many participants also found that direct input methods led to frequent occlusion of the display (more so than with the mouse). People who lean forward to rest on the table may block the part of the tabletop closest to them. Resting a hand on the table may block the display, or even lead to an accidental selection of an object (on a touch-sensitive display). Because a tabletop display affords interaction in a similar fashion to a regular tabletop, people are likely to rest on the surface, so this behaviour must be incorporated into the design of displays and tabletop applications.

Occlusion of the display also occurs when simple selection takes place with a hand or stylus: this was commented upon by two stylus users (in the second Memory Game) and by three DiamondTouch users (in the Search Game). As well, the mouse (or similar indirect input device) must rest

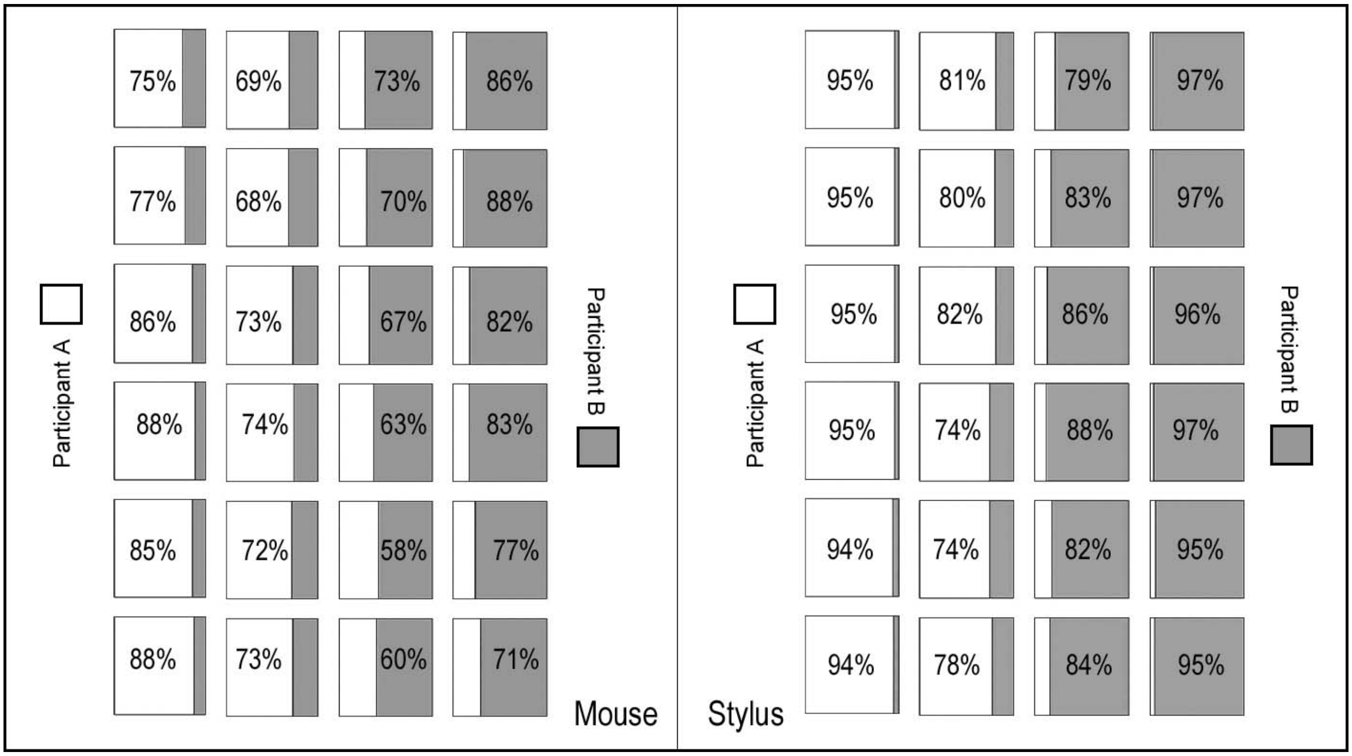

Figure 3:Division of card selection in the Memory Game, for both mouse and stylus conditions. Numeric percentages are shown only for the majority of the total, and are shaded according to the participant who made the most selections of that card.

conveniently close to the user, which may entail placing it directly onto the tabletop surface. The mouse may occlude some elements on the display, unless the tabletop is sufficiently large to allow for blank space. Note that even when there is space for the mouse at the edges of the display, users may drag the mouse onto the display area. We observed this behaviour repeatedly in our second Memory Game experiment, and this problem was reported by one participant in a post-condition questionnaire, "[I] sometimes moved the actual mouse (not the cursor) over one or more of the cards, which momentarily disrupted my view."

TERRITORIALITY

In order to coordinate actions on a shared tabletop display, users may partition their interaction by space and/or by time. *Territoriality* refers to the group members' division of the workspace into regions: for example, into areas that "belong" to each individual. Territoriality has been thoroughly explored in Scott et al.'s tabletop research [13]; what we add to their work are some insights about the specific effects of input technique on territoriality.

In both Memory Game experiments, participants were able to reach all cards, and both participants were free to turn over any cards they wished (although only two cards could remain turned over at any one time). Thus, both people were free to partition the work and the display in any fashion they chose.

We analyzed territorial behaviour in the second Memory Game experiment. We noticed that the tabletop was divided very cleanly across the mid-line when *both* styli and mice were used. However, this division was much more marked in the stylus condition. Figure 3 below, for each card, the percentage of total clicks performed by the user who made the *majority* of clicks for that card. For example, if a card was clicked 50 times, and Participant A clicked on it 35 times (and B clicked 15 times), we would show 70% in the white-colored portion of the card (since white represents Participant A, and grey represents B).

For both the mouse and the stylus conditions, the majority of selections per card were performed by the person sitting on the side of the table *closest* to that card. When using mice, the most even divisions occurred in the centre-most rows of the table. For example, two cards in these rows are quite evenly split, at 52/48 percent and 60/40 percent. On the far edges of the table, the divisions were more extreme, ranging from a 71/ 29 percent split to a 88/12 percent split.

This division was even more pronounced under the stylus condition. The most equitable divisions also took place in the centre-most rows, with the most even split being 74/26 percent (more uneven than the mouse interaction). On the far edges of the table, the inequity is more dramatic: the divisions range from 94/6 percent to 97/3 percent.

Our results agree with those found by Tse et al.[19], in which users of multiple mice on a single desktop computer also partitioned the workspace to avoid interference. Similarly, Everitt et al. [4] found that users of a touch-sensitive display employed various strategies to avoid collisions, such as verbal negotiation or explicit turn-taking.

We also observed some interesting territorial behaviors during this study: participants would sometimes place their cursor or stylus on a card, and then tell their *partner* to flip it (rather than flipping the card themselves). This indicates that those artifacts are seen as belonging to the other individual, and may not be interacted with even when it is convenient to do so.

Overall, these results clearly demonstrate how hesitant people were to reach across the tabletop to make selections. What is unclear from our tabletop experiments is how much of this reticence is due to physical obstacles (e.g., effort required to reach across tabletop), and how much is due to territoriality (e.g., belief that those far objects "belong" to the other person). Obviously, more effort is required to use a direct input device, rather than an indirect input device, to reach far objects. However, this same territorial division occurred with both styli and mice. Even when the object was within reach of a mouse cursor, the item was sometimes not selected when it was seen as being outside one's own territory.

Participants' comments shed some light on this question; after they had completed both experimental conditions (mouse and stylus), they were asked "Were you more likely to interact with the objects on your 'partner's side' of the table when using the mouse or stylus?" Not surprisingly, 20 out of 24 participants chose 'mouse.' When we asked for justification, the most commonly-cited reason was ease of use (not having to reach across the table). However, six participants provided reasons based on coordination: specifically, territoriality and wanting to avoid physical collisions with their partner. Examples included, "Don't feel like you are intruding on their 'space.'"; "With pointer I don't feel any invasion to…partner's territory, but with my hand yes."; and "Because it was easier to point at cards on his side without the potential of bumping our hands/stylus in the process." This suggest that there is some desire to partition the physical space that goes beyond simple ergonomics, and would exist even if all parts of the display were easily accessible to both partners.

PHYSICAL INTERFERENCE

We observed concerns over physical collisions much more strongly in the Search Game study. The tabletop was much smaller, and participants were required to select objects on all parts of the table: this design precluded any explicit territorial behaviour. In addition, participants were trying to finish the game faster than their partner; this aspect made turn-taking undesirable and required rapid physical movements. After they used the touch-sensitive display, we asked them, "Were there any aspects of using the touch screen that interfered with your ability to interact with the display, with the task, or with your partner?" Four participants stated that they had physical collisions; one person said, "Well, we stabbed each other once, so I was more hesitant to move my finger if he was already moving toward a square." Our post-session questionnaire asked whether the mouse or the touch-based input was preferred: a minority (9/24) preferred the mouse. Of those who preferred the mouse, two people cited a dislike of physical collisions; one stated that "…there was no chance of collision with the partner's hand." Across all questionnaires, six participants expressed concern about physical interference and collisions. Parallel, high-speed interactions with a direct input device would likely lead to such collisions, and therefore should be avoided when possible.

In summary, our studies demonstrated that a physical pointer can be seen as more invasive than a virtual pointer. In addition, users of a direct input device may be concerned with bumping into their partner. In these cases, users are likelier to divide the display into distinct territories, where possible.

AWARENESS OF INTENTION AND ACTION

A notable feature of working on a tabletop display was the ease with which users communicated actions and intentions in a collaborative setting. Communication of actions and intentions between participants is an important component for successful collaborative environments. Because we communicate our intent naturally in our everyday lives, we should leverage these skills when developing co-located collaborative technologies.

Results from our first Memory Game study suggested that the use of the stylus, in conjunction with the tabletop display, helped to promote awareness of intention and action. Two participants commented that "the position of the pen enabled me to guess what my partner wants us to do" and "the stylus was better in that it was less confusing as to who was pointing at what when there were two input devices". In general, using a direct input device made it easier for the participants to see and anticipate their partner's actions. In contrast, it was much more difficult to see and track virtual gestures such as mouse cursor movement with an indirect input device. For instance, when using two mice, participants frequently encountered collisions. Two participants commented: "sometimes we made mistakes, both clicking on a card as the 'first' card" and "my partner and I clicked at the same time while using different mice".

Because of the findings in this first study, we selected observable behaviors that we felt would indicate increased awareness between partners, and measured them in our second and third studies.

AWARENESS OF INTENTION

We designed our follow-up studies based on our initial Memory Game experience. Because we had observed collisions in this study, we decided to re-run the game and count the number of collisions occurring under mouse and stylus conditions. Our initial study suggested that we would see more collisions when participants used a mouse.

Interestingly, we did not see a replication of this behaviour in our follow-up experiment. As described above, the participants partitioned the display into distinct territories and employed turn-taking behaviors. Because of their effectiveness in avoiding interference, we saw few collisions in either mouse or stylus conditions—a total of 64 and 68, respectively, over *all* games. We can conclude two things from this experiment: people are very efficient at coordinating their behaviour on tabletops, and that the number of collisions may not be a useful indicator of awareness of intention for some tasks.

Despite these quantitative results, the majority of our participants (17 out of 24) felt that the stylus was better than the mouse at informing their partners of their intentions. Therefore, it is likely that there are more factors at play than mere "collision avoidance." We are in the process of designing further studies to determine what these measurable factors might be.

AWARENESS OF ACTION

The second behaviour that we measured was the amount of time taken to respond to a partner's action. We created the Search Game to record time intervals between one participant's discovery (and selection) of an item and their partner's discovery (and selection) of that same item. Our hypothesis was that the large physical gestures afforded by direct input would make the selection more obvious, and thus a partner would notice (and respond to) a selection faster than with indirect input.

This hypothesis turned out to be correct. We measured the time interval between one person's discovery of the desired image, and the second person's discovery of that same item; the faster the response, the shorter the time. A two-way mixed ANOVA was run for input device (mouse, touch) and for which condition was experienced first. The results revealed a significant main effect for input device ($F_{1,10}$=6.06, p=.034, η^2=.37) with participants having faster intervals when using touch input ($\bar{x}$=1508ms) than when using mouse input ($\bar{x}$=2830ms). No significant interaction effect was found between input device and first condition and no main effect was found for first condition ($F_{1,10}$=4.00, p=.07, η^2=.29) and ($F_{1,10}$=.01, p=.93, η^2=.001, respectively).

Based on these results, we can conclude that one of the strengths of direct input is its ability to communicate actions to collaborators in a tabletop setting. This may indicate that the obviousness of the hand gesture provided better direction to the partner. Participants' comments bore out this observation: when asked which input method (mouse or touch) was more helpful in communicating what their partner was doing, 20 out of 24 people selected "touch." Comments included: "It was easier to keep track of where my partner's hand was than where the mouse cursor was", and "You were more aware of their hands than the cursor when they used the mouse."

ADDITIONAL OBSERVATIONS

We were able to draw some additional general conclusions about awareness of intention and actions from this set of studies. For example, indirect input devices require attention, which can decrease awareness of one's partner. Even when using a mouse, the lack of proprioceptive feedback makes it necessary for them to focus on the cursor in order to interact with the table. As a result, people in our studies found it difficult to gesture effectively with the mouse cursor while looking at their partner. Furthermore, participants could not interpret a mouse gesture without shifting visual attention between the display and their partner. To provide more awareness information on a tabletop display, mouse cursors could be modified (i.e. made larger or more distinct). However, given that the mouse is an indirect input device, its operation is in a different physical location than the cursor, and thus the aforementioned problems will likely persist.

Finally, as evidenced in these studies, direct input on tabletop displays helps to promote natural interactions. When people used styli and hands, these interactions occurred in the surrounding physical space. As such, users were able to transfer everyday knowledge of how to interact with both the physical world and with other people to the tabletop display environment. These innate interpersonal communication skills help us to interact in a rich manner and take advantage of intuitions to gain awareness of others' intentions and actions when using digital media.

SUMMARY: PROS, CONS, AND CONSIDERATIONS

Our studies highlighted a number of ways in which direct and indirect input devices affected collaboration around a tabletop. These results have implications for practitioners, in particular those who design tabletop applications and those who incorporate tabletop displays into their environments. We summarize our key findings below, in terms of their advantages, drawbacks, and any special considerations that must be made when choosing an appropriate input device:

DIRECT INPUT DEVICES

Pros:

- support natural, fluid gestures
- support coordination through greater awareness of intention and action
- allow for noticeable gestures

CONS:

- user may become tired
- items on far side of table are difficult to reach
- noticeable gestures may be distracting
- input device may obscure display
- users may physically collide in workspace

CONSIDERATIONS:

- device may be seen as "invasive" into partner's territory on display. This may improve coordination, or may unnecessarily restrict activity in some regions of the display

INDIRECT INPUT DEVICES

Pros:

- allow items on far side of table to be easily accessed
- do not require much physical effort to use
- may be more familiar to users
- small pointer does not obscure elements on display

CONS:

- reduce the amount and range of gestures
- subtle gestures may go unnoticed
- lesser support for awareness of intention and action may impede coordination and collaboration
- multiple cursors may be distracting or confusing

CONSIDERATIONS:

- space must be left on tabletop to accommodate device (close to user)
- user likelier to cross territorial boundaries with indirect device than with direct device

CONCLUSIONS AND FUTURE WORK

As we continue to embrace new technologies in our everyday lives, tabletop displays hold potential for supporting collaborative interactions. In order to realize the potential for tabletop displays, we must be able to make informed choices about appropriate types of input. Our results demonstrate how different input device parameters can impact users' interactions.

Overall, direct input on tabletop displays supports natural gesturing and allows users to easily notice their partner's actions. In addition, it can provide rich interpersonal interactions, enabling users to both impart and understand each other's intentions seamlessly. The naturalness of these interactions makes it possible to utilize our existing capabilities for interaction in the physical world in the digital domain. This, in turn, allows us to leverage users' inherent communication and interaction skills for use in new media environments.

Indirect input devices, on the other hand, have ergonomic advantages. They may be more comfortable and allow easy access to all regions of the tabletop. Indirect devices can prevent physical interference and avoid occlusion of the display. These qualities can be taken advantage of in tabletop displays as well as other types of single display groupware.

Our ongoing work will continue to investigate how people interact collaboratively around a table, and how we can effectively support this process through technological innovation. We plan to investigate which tasks may be well suited for a tabletop display and how to best design these multi-user environments. In the short term, we plan to explore issues related to new input techniques, to find more meaningful measures for awareness of intent, and to examine new metaphors for tabletop interfaces.

ACKNOWLEDGEMENTS

We would like to thank Mitsuibishi Electric Research Labs for funding this research and donating usage of the Diamond Touch table. We would also like to thank NSERC and Dalhousie University for also supporting this project. Finally, we would like to the other members of the EDGE Lab for their suggestions and feedback on this project.

REFERENCES

1. Abowd, GD. and Mynatt, ED. (2000) Charting past, present and future research in ubiquitous computing. ACM Transactions on Computer-Human Interaction, 7(1), 29-58.
2. Deitz, P. and Leigh, D. (2001). DiamondTouch: A Multi-User Touch Technology. In Proceedings of UIST 2001, pp. 219-226.
3. Eden, H., E. Hornecker, and E. Scharff. (2002) Multilevel Design and Role Play: Experiences in Assessing Support for Neighborhood Participation in Design. In Proceedings of DIS 2002, pp. 387-392.
4. Everitt, K., Forlines, C., Ryall, K., Shen, C. (2004). Observations of a Shared Tabletop User Study. Interactive Poster Abstract, CSCW 2004, Nov. 6-10, 2004, Chicago, IL, USA.
5. Fox, A., Johanson, B., Hanrahan, P., and Winograd, T. (2000). Integrating Information Appliances into an Interactive Workspace. IEEE Computer Graphics and Applications, 20(4), pp. 54-65.
6. Hourcade, J.P., and Bederson, B.B. (1999) Architecture and implementation of a Java package for multiple input devices (MID). Tech Report HCIL-99-08, CS-TR-4018, UMIACS-TR-99-26, Computer Science Department, University of Maryland, College Park, MD.
7. Krueger, W. and Frohlich, B. (1994). The Responsive Workbench. *IEEE Computer Graphics and Applications*, *14*(3): p. 12-15.
8. Kruger, R., Carpendale, M.S.T., Scott, S.D., and Greenberg, S. (2003). How People Use Orientation on Tables: Comprehension, Coordination and Communication. In Proceedings of the ACM Group 2003 Conference, November 2003, pp. 369-378.

9. Kruger, R., Carpendale, M.S.T., and Greenberg, S. (2002). Collaborating over physical and electronic tables. In Extended Abstracts of CSCW 2002. p. 139-140.
10. Patten, J., Ishii, H., Hines, J., and Pangaro, G. (2001). A wireless object tracking platform for tangible user interfaces. In Proceedings of CHI 2002. p. 253-260.
11. Rauterberg, M., Bichsel, M., Leonhardt, U., and Meier, M. (1997). BUILD-IT: a computer vision-based interaction technique of a planning tool for construction and design. In Proceedings of INTERACT '97. p. 587-588.
12. Rekimoto, J. (2002). SmartSkin: an infrastructure for freehand manipulation on interactive surfaces. In Proceedings of CHI 2002. p. 113-120.
13. Scott, S.D., Carpendale, M.S.T, and Inkpen, K.M. (2004). Territoriality in Collaborative Tabletop Workspaces. In Proceedings of CSCW 2004, Nov. 6-10, 2004, Chicago, IL.
14. Scott, S.D., Grant, K.D., and Mandryk, R.L. (2003). System Guidelines for Co-located, Collaborative Work on a Tabletop Display. In Proceedings of ECSCW '03, September 2003, pp. 159-178.
15. Shen, C., Lesh, N., Vernier, F., Forlines, C., & Frost, J. (2002), Sharing and Building Digital Group Histories. In Proceedings of CSCW'02, pp. 324-333.
16. Ståhl, O., Wallberg, A., Sderberg, J., Humble, J., Fahln, L.E., Lundberg, J., Bullock, A. (2002). The Pond: Information Exploration Using an Ecosystem Metaphor. In Proceedings of ACM Collaborative Virtual Environments (CVE) 2002.
17. Streitz, N., GeiSler, J., Holmer, T., Konomi, S., MfillerTomfelde, C., Reischl, W. Rexroth, P., Seitz, P., Steinmetz, R. (1999) i-LAND: An interactive landscape for creativity and innovation. In Proceedings of CHI 99, 120-127.
18. Sugimoto, M., Hosoi, K., Hashizume, H. (2004). Caretta: A System for Supporting Face-to-face Collaboration by Integrating Personal and Shared Spaces In Proceedings of CHI 2004, Vienna, Austria, pp.41-48.
19. Tse, E., Histon, J., Scott, S., and Greenberg, S. (2004). . Avoiding Interference: How People Use Spatial Separation and Partitioning in SDG Workspaces. In Proceedings of CSCW 2004, Nov. 6-10, 2004, Chicago, IL.
20. Ulmer, B., and Ishii, H. (1997) The metaDESK: Models and prototypes for tangible user interfaces. In Proceedings of UIST 97, 223-232.
21. Underkoffler, J., and Ishii, H. (1999) Urp: A luminous-tangible workbench for urban planning and design. In Proceedings of CHI 99, 386-393.
22. Weiser, M. (1991) The computer for the 21st century. Scientific American, 265(3), 94-104.
23. Wellner, P. (1991) The DigitalDesk Calculator: Tangible manipulation on a desk top display. Proceedings of UIST 91, 27-33.
24. Wu, M. and Balakrishnan, R. (2003). Multi-finger and whole hand gestural interaction techniques for multi- user tabletop displays. In Proceedings of UIST 2003. p. 193-202.