Collaboration Around a Tabletop Display: Supporting Interpersonal Interactions

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ABSTRACT

This paper explores the use of a tabletop display to support collaboration. The research goal was to investigate participants' collaborative interactions while they worked cooperatively around a tabletop display. In particular, non-verbal interactions of participants were examined to elucidate issues surrounding awareness of intent. Two different input device strategies were explored for interaction with the tabletop display. Stylus and mouse based interaction models were developed to allow multiple people to simultaneously interact with the system using either one or two devices. The results demonstrated that users exhibited a high degree of physical interactivity when working around the table and that the stylus-based approach encouraged non-verbal communication between participants. In particular, physical gestures and eye contact afforded by the tabletop enhanced users' awareness of their partner's intent. Overall, we found that the tabletop display was a natural medium to support collaboration and that the stylus was an effective device to support seamless interactions.

Keywords

CSCW; tabletop display; collaboration; single display groupware; input device; mouse; stylus; pen-based input.

INTRODUCTION

The traditional desktop computer with its mouse, keyboard, and monitor has been the accepted standard for computing over the past few decades. While this conventional model of computing is still predominant, the genre of interactive technologies available has expanded considerably to include a host of other devices such as handheld computers, laptops, electronic whiteboards and tabletop displays. These new technologies reflect the desire to develop tools that better support the needs of users and the tasks they want to perform.

Projecting a computer display onto the surface of a table has been explored by many researchers [18,14,15,8,16]; however, its use has been limited outside of research labs. From a non-technology perspective, a table provides an excellent environment to support group interactions and is the primary piece of furniture used when people work together. It is important to recognize that tables afford different kinds of interactions and uses than desktop computers do. While desktop computers are by nature individual and personal, the size and wide viewing angle of a tabletop naturally supports small groups in a more public manner. As a result, interfaces and interaction styles that are effective on desktop computers may not adequately support tasks on a tabletop computer display. At the heart of these differences is the way that people interact with the technology and with each other.

Although researchers have demonstrated many potential uses for tabletop displays, we still lack an understanding of how people interact with them and how to best design interfaces which maximize their potential. Abowd and Mynatt have identified natural interfaces as an important theme for research in ubiquitous computing [1]. Our research goal was to investigate collaboration around a tabletop display, paying specific attention to users' natural interactions in this medium. Much of our focus was on the interpersonal communication between users. We were interested in the ease with which people could integrate their knowledge of interaction in the physical world into their utilization of a tabletop display.

The research described in this paper explores collaborative usage of a tabletop display and examines input device strategies to effectively support multiple people working together around a table. We first present previous research related to supporting co-located collaboration and tabletop display systems. We then describe our empirical study and the results obtained. Next, we discuss how these results impact users' awareness of intent when working collaboratively. Finally, directions for future work are presented.

RELATED WORK

Weiser's vision of ubiquitous computing included the notion that technology should be designed to fit into our natural human environment [17]. As such we shouldn't 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 in ubiquitous computing [1]. In particular, interfaces should support and utilize the way humans interact with the physical world.

The research area of Single Display Groupware (SDG) examines issues related to multiple people working together around a shared display [13]. These issues include creating shared interactive displays [9]; and providing multiple peripherals on a shared computer [13]. Research has also explored the nature of collaborative interactions in SDG environments [10,11]. Effective design of SDG environments have been shown to increase motivation and engagement, while helping users develop a better shared understanding of the workspace [10, 11].

Tabletop Systems

Desks and tables are used extensively to work with physical artifacts such as paper, books and pens. However, a great deal of our work is conducted using desktop computers. Previous literature suggests that tabletop display systems can bridge the physical and digital environments. Wellner's DigitalDesk introduced the idea of augmenting a physical desk with electronic properties [18]. More recently, Ulmer and Ishii's research on the MetaDESK has explored this notion further with a focus on physical interaction to manipulate the digital environment [15]. Other research in tabletop systems has includes: the Responsive Workbench [6], Hi-Space [7], URP [16], InteracTable [14], and SenseTable [8].

Tables are frequently used to support small groups of people working together. Researchers have suggested the potential of tabletop displays to support collaboration. The InteracTable was designed to support cooperative work of dynamic teams [14]. Patten et al. have suggested that the SenseTable affords collaboration between users by allowing people to interact simultaneously [8]. The Interactive Workspace at Stanford University supports a many-many interaction structure by developing integrated applications for multiple people using multiple devices [19]. The Mitsubishi Electric Research Lab has developed the OpTable to explore single-display multi-user systems for sharing information in face-to-face settings [12].

Like the many installations of tabletop displays, there are just as many approaches to input. Wellner's Digital Desk [18] system uses a vision based-system to track the user's finger and enable pointing at objects in the system. The HI-SPACE [7] system also uses a vision-based approach to track hand gestures while the I/O bulb [16] system uses vision to track physical objects. The InteracTable [14] uses a touch sensitive display, enabling people to write or draw on the table with a pen and interact via finger or pen gestures. The metaDesk [15] and Sensetable [8] use tangible objects to interact with digital information. Many other tabletop installations utilize traditional desktop input devices such as mice and trackballs.

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, a lack of understanding concerning users interactions with the tabletop display and various input strategies also clouds the decision as to which input device would be most appropriate. One should consider interpersonal communication when choosing which input device to use in order to support collaboration.

Workspace awareness

Understanding workspace awareness can help to shed light upon users' interpersonal communication in collaborative settings. Gutwin and Greenberg define workspace awareness as the understanding of another person's interaction with a shared workspace [4]. This differs from the traditional definition of awareness in that it involves awareness of people and how they interact with the workspace instead of awareness of the workspace itself. Gutwin organizes elements of workspace awareness into eight categories. When investigating collaboration around a tabletop display, the categories of *what* (action, intention, and artifact) and *where* (location, gaze, view, and reach) are particularly relevant. Information related to workspace awareness is primarily gathered from the other person's body in the workspace including position, posture, and movement of head, eyes, and arms [4]. In addition, information related to users' intent is inferred from their gestures and visual actions.

METHOD

We conducted an empirical study to explore collaborative interactions around a tabletop display. Participants used mice and styli to cooperatively play a memory game.

Participants and Setting

Twenty-four university students (12 male and 12 female) volunteered to take part in this study. All participants frequently used computers for work and leisure and rated themselves as being very comfortable with computers.

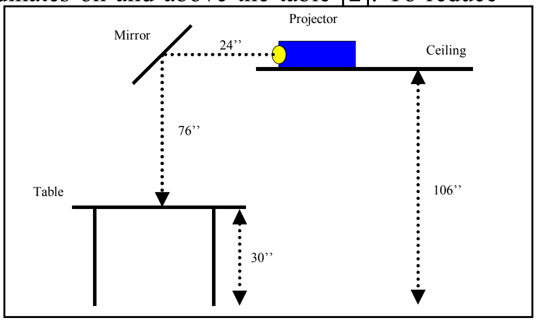
System Implementation

The tabletop system was top-projected and consisted of a 150cm by 80cm white laminate surface onto which output from a Pentium III 500 MHz computer was projected. The projected display was 103cm by 79cm with a resolution of 1024 by 768. (see Figure 1).

Two USB mice were used to provide support for multiple inputs. The MID toolkit [5] was used to capture events from both mice independently. Because mouse movements are dependent on the orientation of the mouse, modifications at the software level were made to correctly map the input depending on which side of the table the mouse was used. When only one mouse was present, a button was provided so that the mouse could be passed across the table. When two mice were used, each mouse was oriented appropriately to its respective user.

To provide styli input, a Polhemus Fastrak with styli receivers was used. A Fastrak is a six-degrees-of-freedom magnetic tracking device that can detect the position and orientation of up to four input devices. We developed Java-based software to process the Fastrak information sent to the serial port. Without calibration, the Fastrak does not provide sufficiently accurate information about the location of the pen. To calibrate the stylus we used a fourth-degree polynomial fit from measured data to actual coordinates on and above the table [2]. To reduce magnetic interference, a wooden table was used and we avoided placing metallic or magnetic objects of any kind

(a)



(b)

Figure 1. The specifications of the tabletop system used are shown in (a), while (b) shows two people working with the system in the one-stylus experimental condition. Note that participants sat on opposite sides of the table.

on and around the table while the Fastrak was in use. The tracker cube was attached to a 7.5cm X 7.5cm X 1.2cm block of wood using plastic screws and mounted underneath the table in the centre using double-sided tape. By placing the cube in the centre of the table, we minimized the average distance to the each possible screen coordinate and thus improved accuracy. A tap on the table was recognized when the pen tip moved from above the table to within 0.01cm of the table. In order to tap again, the user had to lift the pen above the threshold and then back down (thus dragging the pen did not create multiple taps). This system is also capable of detecting which side of the table the stylus is being used from based on the orientation of the device.

Software

A ‘memory-style’ game was developed for use in this study. The game involved twenty standard playing-cards being placed face down on the table. These twenty cards contained ten matching pairs which the players were required to find by turning over cards (two at a time). Once two cards were turned over, the system checked to see if the cards were a match (both in terms of number and suit). If the cards matched, the two cards disappeared. If the cards didn’t match, after a brief pause, they were turned face down again. Each time a card was turned over, one point was recorded. The goal of the game was to find all of the matches while minimizing the total number of points.

Figure 2 shows a screen-shot of the game. No restrictions on input were provided for either player so both were able to turn over cards at any time. This allowed the pairs to develop their own strategy for playing the game.

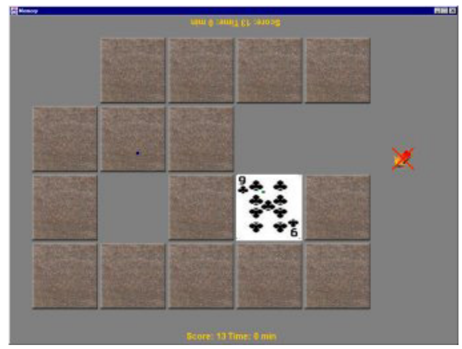


Figure 2. A screenshot of the Memory game software.

Playing cards were used because their orientation would be appropriate for players sitting on opposite sides of the table. Within each experimental condition, three different sets of cards (one for each game) were randomly chosen to reduce repeated viewing of the same cards.

Time was a secondary factor in the game. We were reluctant to use time as a fine-grain measure of performance because its potential to inhibit communication and collaboration. However, a time factor would make the task more challenging. As a result, a course-grain measure of time was used to encourage players to complete the task in a reasonable amount of time. Players were told that they would have five minutes to complete each game but that they would receive a time penalty after three minutes. The time displayed during the game was only shown in minute increments to help prevent it from being a primary focus.

Experimental Design

A within subjects design was used with two independent variables: type of input device; and number of input devices. Experimental conditions consisted of the four different input device configurations: (1) sharing a single mouse; (2) sharing a single stylus; (3) two mice; and (4) two styli. Table 1 shows the four ordering of conditions used which were counterbalanced for position within a session (all conditions appear in each of the four positions within a session), single input device versus multiple input devices (the two single input device conditions were always played together either at the beginning or end of a session), and for mouse versus stylus (within single/multiple input devices, the order of mouse/styli were counterbalanced).

Table 1. Orderings of experimental conditions

Order 1	1 Mouse	1 Stylus	2 Mice	2 Styli
Order 2	1 Stylus	1 Mouse	2 Styli	2 Mice
Order 3	2 Mice	2 Styli	1 Mouse	1 Stylus
Order 4	2 Styli	2 Mice	1 Stylus	1 Mouse

The participants were also categorized into one of three gender pairings: 1) female pair; 2) male pair; or 3) mixed gender pair. Each ordering of experimental condition included one pair from each gender grouping.

The dependent variables analyzed in this study included non-verbal communication (e.g. gestures and eye contact), performance, preference, collaborative interactions, and input device strategy. Performance data were gathered from automatic logging of the participants' interactions in the game. A score was assigned for each of the games to indicate the number of tiles that were overturned unnecessarily when its match had previously been uncovered. The rules for scoring were as follows:

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Let a & b be a matching pair of cards.
Let <x,y> be an ordered pair of cards representing
one turn of play.
A point was scored for card a if:
  • x = a, y ≠ b & a had previously been uncovered
  • x ≠ b, y = a & a had previously been uncovered
  • x = a, y ≠ b & b had previously been uncovered
but, not if:
  • x = a or y = a & a had not yet been uncovered
  • <x,y> = <a,b> or <b,a>
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Procedure

At the beginning of each session the participants signed consent forms and filled out background questionnaires. The background questionnaires gathered information related to general demographics, participants' experience with computers and various types of input devices, and their attitudes towards collaborative use of computers. Participants were then given an introduction to the study, the tabletop display, and the game software. They played a practice game on a desktop computer to become familiar with the Memory game. On the tabletop system, (see Figure 1b) the participants were asked to play three games in each of the experimental conditions. All sessions were videotaped and researchers gathered field notes while session logs documented the players interactions with the game. After playing all four conditions, the players asked completed post-session questionnaires to provide feedback on their preferences about both number and type of input devices for the tabletop.

DISCUSSION OF RESULTS

We present and discuss results related to participants' non-verbal communication, use of multiple input devices, performance, and natural interactions.

Non-Verbal Communication

Non-verbal communication data were gathered from analysis of the video. The data collected included both hand and eye movements. A gesture was defined as a motion with the hand or input device, used to communicate information about a specific artifact in the game. Two researchers simultaneously recorded frequencies of gestures for a pair. Each researcher monitored one participant in the pair and discussed the classification of ambiguous gestures whenever they occurred.

Gestures made when holding the input device were categorized into three classes. First, an *input device gesture* was recorded each time the participant used their input device to gesture. These included pointing at cards with the tip of the pen and positioning the mouse cursor over cards, but not tapping or clicking on cards. Second, an *input device-hand gesture* was recorded each time the participant used the hand holding the input device to gesture. These gestures included pointing at cards with their fingers as well as entire hand movements across several cards (e.g. to indicate a row). Third, an *other-hand gesture* was recorded each time the participant gestured with the hand not holding the input device. In the one input device conditions, *hand gestures* of the participant not holding the input device were recorded in a separate category.

We also gathered information related to how participants used their eyes to communicate with their partner. Researchers recorded the number of times participants looked at each other as well as the number of times these actions resulted in eye contact.

Physical Gesturing

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

The average number of physical gestures observed per session for each condition is shown in Table 2. A significant interaction effect was found for physical gestures across conditions ($F(1,11)=9.64$, $p<.05$). Further analyses revealed that in the one input device conditions, no significant difference was found between the number of physical gestures when using the stylus than when using the mouse ($F(1,11)=2.07$, $p=.179$). However, in the two input device conditions, participants exhibited significantly more physical gestures when using the stylus than when using the mouse ($F(1,11)=25.88$, $p<.001$). Also, when only one input device was present, the partner without the input

Table 2. Average number of physical and virtual gestures exhibited for each session.

# Input Devices		Mouse			Stylus		
		Holding mouse		Other participant	Holding stylus		Other participant
		Mouse cursor[a]	Hand gestures[b]		Stylus gestures	Hand gestures[b]	
1	Mean (SD)	15.0 (8.6)	5.2 (7.2)	50.3 (18.5)	23.3 (18.8)	6.3 (11.6)	40.5 (21.1)
2	Mean (SD)	30.3 (15.2)	14.9 (16.6)	N/A	41.0 (34.5)	14.1 (11.5)	N/A

[a] Mouse cursor represents virtual gestures made with the mouse. The remaining categories represent physical gestures.
[b] This category includes all hand gestures made by the participant holding the input device.

device gestured significantly more than the partner with the input device[1], M=90.8 and M=49.7 respectively (F(1,11)=25.8, *p*<.001).

The results of physical gesturing reveal an interesting yet subtle difference between mice and styli. In general when participants were holding the mouse, they made few physical gestures (see Figure 3). Therefore, in the two-mouse condition, because both partners had a mouse, the amount of overall physical gestures was greatly reduced. However, when the participants were using styli, there was little difference between the number of physical gestures in the one stylus versus two styli conditions.

Another important observation was the participants' level of engagement when only one input device was present. Even though only one person could interact with the system at a time, both players were actively engaged at all times. Previous research on desktop computers reported that when support for only one input device was provided, the partner not in control of the input device was significantly less engaged [10]. This lack of engagement was not found in the current study, as evidenced by the large number of gestures exhibited by the person without the input device.

Physical interaction between participants, when using the tabletop display, was overwhelmingly evident. This high degree of interaction highlights another significant difference between a tabletop display and a traditional desktop system. As observed in earlier research related to supporting co-located collaboration on a desktop computer, the amount of physical gesturing is often minimal [10, 11]. The nature of gesturing observed in the current study was comparable to observations of people interacting with physical media [10].

Virtual Gesturing

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 when using a single mouse was 15 and was 30 when using two mice. However, this type of gesturing still occurs less frequently than the amount of physical gesturing with the stylus, 23 and 41 for the one stylus and two styli conditions, respectively (F(1,11)=3.743, *p*=.079). This difference is marginally significant.

Although virtual gesturing with the mouse cursor was common, it was problematic given the greater 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

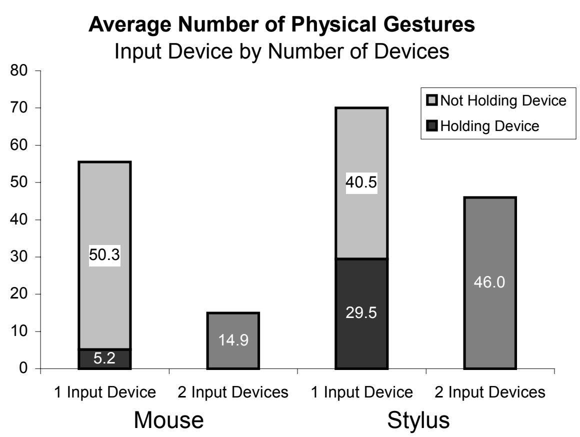

Figure 3. Average physical gestures by condition.

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. At times, players would simultaneously act without an awareness of actions their partner was taking in parallel.

Eye Contact

The videos were analyzed to determine the number of times participants looked at each other and the number of times eye contact was made (see Table 3). No significant differences were found in the number of times that partners looked at each other either in terms of input device (F(1,11)=2.91, *p*=.116) or number of devices (F(1,11)=).75, *p*=.404). However, a marginally significant interaction effect was found for the number of times that partners made eye contact (F(1,11)=4.69, *p*=.053). Further analyses revealed that when using two input devices, no significant difference was found (F(1,11)=.046, *p*=.834), yet when only one input device was present, significantly more eye

[1] Gestures for the partner with the input device included both physical gestures made with the stylus and virtual gestures made with the mouse cursor.

contact was made when using the stylus as opposed to the mouse (F(1,11)=8.76, *p*<.05).

This result could be attributed to the fact that when using a mouse, it was necessary to pay closer attention to the display in order to track the mouse cursor. When using one input device, it was especially important for partners to communicate with each other in order to collaborate. As a result, even though the number of times partners looked at each other didn't change, they may have had a decreased awareness of each other and therefore not made eye contact as easily. One participant commented, "you don't have to look at your stylus to move to a location, but for a mouse you have to look at the cursor constantly to make sure to reach the target, which is distracting".

One noteworthy result was the large number of instances where partners looked at each other. In the current study, participants looked at each other an average of 100 times in a 20-25 minute session. In an earlier study, where participants played collaboratively on a desktop with support for multiple input devices, partners looked at each other less than 10 times, on average, in a 30-minute session [11]. This contrast illustrates how the tabletop display can promote and enhance collaborative activities.

Table 3. Average number of times partners looked at each other and made eye contact with each other.

# Input Devices		Mouse		Stylus	
		Looking	Eye contact	Looking	Eye contact
1	M	24.17	4.75	30.08	9.00
	SD	24.35	8.06	26.38	10.53
2	M	19.25	5.67	26.42	6.08
	SD	17.92	6.20	22.62	8.45

Multiple Input Devices

The videos were analyzed to determine the number of times participants passed the input device when only one was present. Control of the mouse was passed only between games with the exception of two pairs who each passed control once during a game. Similarly, for the stylus, all but two pairs only transferred control of the input device between games. The two pairs that did transfer control of the stylus within games, did so a significant number of times (50 and 60 times). In the two input device condition, both participants interacted equally with the game. When using two mice, there was an average difference of 4.8 more cards turned over by one player in the pair. For styli, this difference was 5.2 cards. The number of cards turned over in a game ranged from 32 to 62. The small difference in player interaction shows both participants contributed significantly when using both mice and styli.

From the post-experiment questionnaire, only three of the 24 participants preferred to share one input device. A Chi-Square analysis revealed a significant preference for multiple input devices when playing with a partner (χ^2(1,N=17)=0.00, *p* < 0.01). Participants commented that it provided more flexibility and that it is "more fun when everyone can play". Several pairs also commented that when support was provided for multiple input devices they would prefer to use a stylus to a mouse. The K-S one-sample test revealed marginally significant results for the stylus being an easier device to use (Z=1.263, *p* = 0.082) and a more natural input device (Z=1.324, *p* = 0.060) than a mouse for interaction on a tabletop display.

Performance

Data from the computer logs were analyzed to measure performance (see Table 4). No significant differences were found in the players' scores for either type of input device (F(1,11)=1.276, *p*=.283) or number of input devices (F(1,11)=1.588, *p*=.234). However, a significant correlation was found between the number of gestures in a session and the score for that session (Pearson Correlation=-.335, p<.05). A higher number of gestures correlated to better performance (i.e. a lower score). An increased number of gestures may have enabled partners to communicate and collaborate better, which would improve performance.

High variability in scores and the fact that memory was a defining factor for success in this application may have contributed to minimal differences in performance. Our expectation was that performance differences observed would be attributed to differences in interpersonal communication and not a direct result of the choice of input device. Given that participants were comfortable with both the mice and the styli, that the interaction required was trivial, and having no speed requirements or accuracy constraints, meant that input device had very little impact on performance in the game.

Table 4. Average performance scores by experimental condition. Score was calculated by allocating one point for each card turned over unnecessarily when its match had previously been uncovered.

		Mouse	Stylus
1	M	30.00	29.83
	SD	13.34	14.50
2	M	36.25	30.58
	SD	13.42	13.57

Natural Interactions

One of the most compelling results of this study 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, one of the most natural interactions, 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 they would when interacting around a traditional table, the participants instinctively leaned in and rested their arms on the table as they engaged in the activity, especially when using styli. 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 also promoted natural interactions around the tabletop display. As reported previously, participants 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"

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 comfortable using mice 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 felt it easier to sit in an awkward position, than to take the necessary time to configure their physical setup.

Rather than using a stylus or a mouse, 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 projected tabletop system, the first thing they want to do is touch it to interact with it. A touch sensitive surface also provides the freedom of touching it with a hand or an object, depending on the interaction required (i.e. if more precision is required a stylus-like object could be used). At first glance this would seem to be a superior interaction strategy. However, there are many disadvantages to a touch sensitive display. Most implementations of touch sensitive surfaces only support one touch at a time. This is a serious restriction, especially for collaborative interactions. Furthermore, tables in the physical world are used as placeholders for objects. Things 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. One participant commented that it was "nice to be able to point with your finger and not activate anything". Many participants also rested their fingers on artifacts, with no intention of selecting them. Additionally, since users frequently leaned on the tabletop, it was important to not interpret this contact as an interaction with the system.

AWARENESS OF INTENT

The most notable feature of working on a tabletop display may be the heightened ability to communicate intentions between users in a collaborative setting. Communication of intentions is a critical 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.

Establishing a shared understanding can benefit a collaborative process and help promote awareness of intent. Many of the observations from this study suggest that a tabletop display can help facilitate a shared understanding. The participants in this study frequently used deictic references when communicating with each other, particularly when they were referring to artifacts in the game, such as "that one over there". Clark and Brennan's principle of least collaborative effort states that "in conversation, the participants try to minimize their collaborative effort – the work that both do from the initiation of each contribution to its mutual acceptance" [3, p. 135]. By this principle, the participants' frequent deictic references suggest that they had a high level of mutual understanding during the game; thus, more elaborate dialog was not necessary. This shared understanding was facilitated by the tabletop environment, which provided a shared visual activity surface and a face-to-face context. Participants commented to this effect saying that it was "easier to communicate with the other player to show where to go and it was more like playing a real game".

The common visual surface of the tabletop display is horizontal, and as such, people can sit across from each other. As previously discussed, this configuration encourages a high degree of interactivity between the participants, especially in terms of physical gestures. Figure 1b illustrates two participants engaged in the task with the tabletop display. An increase in physical gestures can help promote awareness of a partner's intent. Because seeing a partner's hand movements required only a small shift in gaze, participants were encouraged to gesture frequently. Also, since the participants sat across from each other it was natural to make eye contact. Increased eye contact revealed that it was easy for users to grab the attention of their partner and convey intentional information.

The use of the stylus, in conjunction with the tabletop display, helped to promote awareness of intent. 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 stylus 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. For instance, when using two mice, participants 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".

Awareness of actions was impacted by drawbacks of the mouse. For the person using the input device, the lack of proprioceptive feedback made it necessary for them to focus on the mouse cursor in order to interact with the table. As a result, it was 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. larger or more distinct). However, the mouse is a relative device and its operation is in a different physical location than the cursor, thus the aforementioned problems will likely persist.

Finally, as evidenced in this study, the tabletop display system helped promote natural interactions. When using styli, these interactions occurred in the surrounding physical space. As such, users were able to transfer to the tabletop display environment everyday knowledge of how to interact with both the physical world and with other people. 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.

CONCLUSION & FUTURE WORK

As we continue to embrace new technologies in our everyday lives, tabletop displays hold great potential for supporting collaborative interactions. The results from this study reveal how people interact around a tabletop display and that tabletop systems promote increased gesturing, interpersonal interactions, and communication. Allowance for the possibility of such rich interactions enables users to both impart and understand each other's intentions seamlessly. The use of a stylus further enhances the experience of using a tabletop display by making it possible to utilize our existing capabilities for interaction in the physical world in the digital domain.

We have shown that by effectively supporting users' natural interactions, we can provide a seamless bridge between physical and digital environments. Such designs help leverage users' inherent communication and interaction skills for use in new media environments.

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. In the short term, we plan to explore user interface issues related to design for co-located collaboration. In particular, issues related to orientation, scalability of applications for large screens, extensibility of input device strategies, support for multiple users, and new metaphors for tabletop displays will be investigated.

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