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System Guidelines for Co-located, Collaborative Work on a Tabletop Display

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Abstract. Collaborative interactions with many existing digital tabletop systems lack the fluidity of collaborating around a table using traditional media. This paper presents a critical analysis of the current state-of-the-art in digital tabletop systems research, targeted at discovering how user requirements for collaboration are currently being met and uncovering areas requiring development. By considering research on tabletop displays, collaboration, and communication, several design guidelines for effective co-located collaboration around a tabletop display emerged. These guidelines suggest that technology must support: (1) natural interpersonal interaction, (2) transitions between activities, (3) transitions between personal and group work, (4) transitions between tabletop collaboration and external work, (5) the use of physical objects, (6) accessing shared physical and digital objects, (7) flexible user arrangements, and (8) simultaneous user interactions. The critical analysis revealed several important directions for future research, including: standardization of methods to evaluate co-located collaboration; comparative studies to determine the impact of existing system configurations on collaboration; and creation of a taxonomy of collaborative tasks to help determine which tasks and activities are suitable for tabletop collaboration.

Introduction

Few existing technologies provide the rich, fluid interactions that exist during collaboration involving paper-based media. Typical desktop computers do not effectively support multi-user interaction because of their underlying one-user/one-computer design paradigm (Stewart et al., 1999). As computers become pervasive in society, digital information is often required during collaboration. However, people often convert this information to paper-based media, make modifications, then re-convert back into digital form. Luff et al. (1992) observed an abundant use of paper in computerized workplaces, with considerable redundancy between the informational contents of the paper and computers used in these environments. Translating information from one medium to the other places overhead costs during co-located collaboration, such as the time and effort required to type in annotations made on a paper documents, and the financial and environmental expense of printing and re-printing documents. In order to minimize these costs, improved technology is needed to support interaction with digital media during collaboration.

Advances in display and input technologies have led to a wide assortment of novel systems to support co-located collaboration. These systems range from extensions of the standard desktop computer (e.g., Bier & Freeman, 1991; Stewart et al., 1999), to electronic whiteboards (e.g., Fox et al., 2000; Streitz et al., 1999) and digital tabletop systems (e.g., Wellner, 1993; Deitz & Leigh, 2001). Technology that provides access to digital media on a tabletop can take advantage of the considerable experience people have with traditional tabletop collaboration.

Observations of traditional tabletop collaboration have shown that people's interactions are fluid and dynamic on the tabletop (Bly, 1988; Tang, 1991). Moreover, collaborators tend to be physically animated during these interactions (Scott et al., 2003). To understand how best to support these fluid and dynamic interactions with digital media on a table we need a clear understanding of the interactions that require support and the ability of current technology to provide that support.

Design of digital tabletop systems is currently at a crossroads; technology is maturing, but it is not clear which tabletop system configuration is suitable for each collaborative environment or activity. At a recent international workshop, tabletop researchers were still debating the question: *what is the most appropriate type of tabletop system to build?* Answering this fundamental question could benefit the larger Computer-Supported Cooperative Work (CSCW) community as more researchers begin exploring co-located collaboration.

As of yet, there is no standard configuration for tabletop systems. Researchers investigating software interface issues for tables are often required to design and build their own system. Many researchers have used simple prototypes involving top-projecting a computer display onto a traditional table, covered with a white surface such as a a whiteboard (e.g., Patten et al., 2001; Scott, et al., 2002; Shen et al., 2002). More elaborate systems have been built involving rear-projected tabletop displays (e.g., Cutler et al., 1997; Ullmer & Ishii, 1997) and self-illuminating displays (e.g., Streitz et al., 2002; Ståhl et al, 2002; Kruger & Carpendale, 2002) on custom-built tables. These systems also use a wide variety of input devices, such as mice (Scott, et al., 2002; Kruger & Carpendale, 2002), pens (Grant et. al., 2003), styli and/or direct touch (Shen et al., 2002; Streitz et al., 2002; Ståhl et al, 2002) and tracked physical input devices (Ullmer & Ishii, 1997; Underkoffler & Ishii, 1999; Patten et al., 2001).

Many digital tabletop systems have also been developed for a variety of specific purposes, for example urban planning (Underkoffler & Ishii, 1999) and automotive design (Buxton et al., 2000). However, no comparative studies have been performed to help determine the suitably of these existing systems for generalized use. In order to help researchers and practitioners make informed design decisions related to both system configuration and functionality, we performed a critical analysis of the current state-of-the-art in digital tabletop systems.

This paper first presents the investigation of past and present digital tabletop systems. Next, a set of design guidelines for collaborative tabletop systems that emerged from this investigation is presented. Examples are given of how these guidelines manifest in current system design. Directions for future collaborative tabletop research are then discussed, followed by our conclusions.

Investigating Existing Digital Tabletop Systems

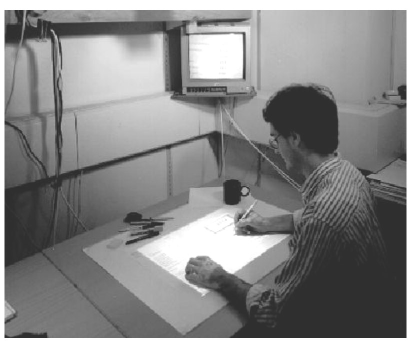
In order to inform the design of future tabletop systems, we investigated state-of-the-art systems, gaining a deeper understanding of how their properties impact co-located collaboration. We gathered data covering user and task requirements. These data sources included:

- Literature on existing digital tabletop systems. A database was developed to classify pertinent details of each system, including details on input (e.g. was concurrency supported, what technology was used), on display (e.g. illumination type, size, height), on end users (e.g. was it collaborative, user domain), and other critical characteristics;
- Human-Computer Interaction (HCI) and CSCW literature on design requirements, implications, and guidelines for co-located CSCW systems;
- CSCW literature involving observational studies of co-located collaboration involving traditional media originally performed for the purposes of informing distributed groupware;
- Relevant literature from the social sciences discussing interpersonal communication and tabletop collaboration;
- Our research experience with tabletop collaboration and digital tabletop

systems, which includes building systems, observing how people use a variety of digital tabletop environments, and performing observational studies of collaboration on traditional tabletops in both casual and formal settings; and

- Outcomes of an international workshop on collaborative tabletop systems.

The results of this analysis revealed four general classes of digital tabletop systems in the literature: digital desks, workbenches, drafting tables, and collaboration tables. Examples of these four systems are shown in Figure 1. Digital desks are designed to replace the traditional desk by integrating paper-based work and interaction with digital media. Workbenches allow users to interact with digital media in a virtual reality environment projected above a table surface. Drafting tables are designed to replace a typical drafter's or artist's table, which have an angled surface and are typically used individually. Collaboration tables are digital tabletops that support small-group collaboration activities, such as group design, story sharing, and planning. The remainder of the paper focuses on the design of collaboration tables, while drawing from the technologies and functionalities of the other table types.



(a)

(b)

(c)

(d)

Figure 1. Examples of the four table types: (a) digital desk (from Wellner, 1993); (b) workbench (from Culter et al., 1997); (c) drafting table (from Buxton et al., 2000); (d) collaboration table (from Ståhl et al., 2002).

Our critical analysis revealed several implications for the design of digital tabletop systems, which have been synthesized into the set of design guidelines presented below. Although these guidelines focus on table systems for collaborative work, we draw on research from the entertainment (Mandryk et al., 2002; Ishii et al., 1999), social (Shen et al., 2002; Grant et al, 2003), and educational (Stewart et al., 1991; Bricker et al., 1999; Scott et al., 2003) domains.

Design Guidelines for Co-located Tabletop Collaboration

Through years of experience collaborating around tables, people have developed skills for interacting with each other as well as with objects on a table. When integrating computer technology into a table, designers must support these skills. Our guidelines are grounded in supporting users' previous experiences with traditional media on a table.

We present eight collaborative design guidelines based on our critical analysis. Additionally, we discuss how current tabletop systems conform to the guidelines. These guidelines assert that technology must: (1) support interpersonal interaction, (2) support fluid transitions between activities, (3) support transitions between personal and group work, (4) support transitions between tabletop collaboration and external work, (5) support the use of physical objects, (6) provide shared access to physical and digital objects, (7) consider the appropriate arrangements of users, and (8) support simultaneous user actions.

Support Interpersonal Interaction

Technology designed to support group activities needs to support the interpersonal interaction at the heart of collaboration. Supporting the fundamental mechanisms that people use to mediate collaborative interactions is a minimal and necessary technological requirement. Interfering with these interactions can cause breakdowns in collaboration, especially when the technology hinders the conversation (Elwart-Keys et al., 1990). For example, when using the idea generation and organization tool COGNOTOR, groups often suffered from communication breakdowns because the system design imposed a communication process that did not support normal co-located conversation (Tatar et al., 1991).

Gutwin and Greenberg (2000) identified several low-level mechanisms, called the mechanics of collaboration, which people use to organize their collaborative activities and interactions. These mechanics increase workspace awareness (Gutwin et al., 1996) by conveying and gathering information about which actions are performed, when they are performed, and who is performing them[1]. It may not be necessary for co-located groupware to explicitly provide software support, such as awareness widgets (Gutwin et al., 1996), for each mechanic, but technology must not interfere with their use. Furthermore, research demonstrating the collaborative importance of gesturing (Bekker et al., 1995; Bly, 1988; Tang, 1991), deictic referencing (Gutwin et al., 1996), and meeting coordination activities (Olson et al., 1992) reinforces the need for co-located tabletop technology to support these mechanisms.

Tabletop environments which accommodate separate, personal displays on the tabletop, such as AUGMENTED SURFACES (Rekimoto & Saitoh, 1999), INTERACTIVE WORKSPACES (Fox et al., 2000), and CONNECTABLES (Tandler et al., 2001) can hamper the use of certain communicative gestures, such as pointing to objects, because other group members may not understand what is being referenced or may not notice the gestures (Bekker et al., 1995).

The tabletop system needs to have an ergonomic form factor suitable for the collaborative activity being performed. For example, the story-sharing PERSONAL DIGITAL HISTORIAN (PDH) tabletop system is modeled after a household coffee table, which provides users with an appropriately informal environment where users can sit on comfortable sofas or lounge chairs while interacting with the table (Shen et al., 2002). In contrast, tabletop systems that have bulky components under the table, such as projectors and mirrors for bottom-projected displays (Ullmer & Ishii, 1997; Agrawala, 1997; Leibe et al., 2000), often require users to stand or sit awkwardly for extended periods of time, potentially impacting the comfort level of users and, the naturalness of the interactions between users. The precise impact of the form factor of these systems on interpersonal interaction requires further investigation.

Support Fluid Transitions between Activities

Technology should not impose excessive overhead on switching between activities performed on a table, such as writing, drawing, and manipulating artifacts. (Bly, 1988; Tang, 1991). For example, paint programs often distinguish between textual and graphical marks, forcing users to explicitly indicate their intention to write or draw. Studies of traditional tabletop design sessions revealed that people do not make this distinction, and rapidly transition back and forth between writing and drawing (Bly, 1988; Tang, 1991). Technology that provides

[1] The *mechanics of collaboration* include: explicit and consequential communication, coordination of action, planning, monitoring, assistance, and protection. Full explanation of these mechanics is beyond the scope of this paper; the reader is referred to (Gutwin & Greenberg, 2000) for more details. However, it is important to mention that, while the mechanics of collaboration are based on studies of co-located and distributed collaboration, they were developed for improving distributed groupware system design. Thus, each mechanic may not have the same relevance for the design of co-located groupware since the communication environment is richer than in a distributed collaboration setting.

little or no overhead to performing or switching between activities would allow users to transition easily between activities, focusing instead on communication.

A universal input device for all tabletop activities would make transitioning between activities smoother. Most current systems associate different input devices with different activities, such as a wireless keyboard for typing and a pointing device for selecting and manipulating virtual objects (Fox et al., 2000; Shen et al., 2002; Scott et al., 2002). Providing only one input mode and device, such as a stylus, ensures that there is no overhead from changing physical devices with shifts in activities. However, having a specialized input device for a particular task can optimize the completion of that task. Thus, the benefits of each approach should be considered carefully, especially with regard to how often transitions between activities that require separate specialized devices will be necessary during the collaborative tasks.

Most current tabletop research systems avoid this issue by focusing on a single type of activity such a sketching or moving objects around the table without providing any capabilities for modifying these objects (Kruger & Carpendale et al., 2002; Shen et al, 2002; Ståhl et al., 2002). One step towards providing seamless transitions between tabletop activities is the development of the BEACH architecture which underlies the INTERACTABLE tabletop system, along with other systems in the INTERACTIVELANDSCAPE (I-LAND) environment (Streitz et al., 1999). BEACH allows users to use pen gestures on the tabletop interface to perform certain frequent actions, such as rotating objects or making informal annotations on the table. While a wireless keyboard is still provided for more extensive text input, these pen gestures help users continue making interactions directly on the table for several different activities, thus, effectively supporting the users' transitions between activities.

Support Transitions between Personal and Group Work

Previous research has shown that people are adept at rapidly and fluidly transitioning between individual and group work when collaborating (Elwart-Keys et al., 1990; Mandviwalla & Offman, 1994). During a study of tabletop collaboration involving traditional media, Tang (1991) observed that users often maintain distinct areas on a tabletop workspace in order to mediate their interactions with the task objects and with each other. Allowing users to maintain these distinct areas may facilitate the transitions between individual and group work. However, the shape of a tabletop system may influence its ability to provide distinct workspaces. A study on seating preferences in a school library showed that students tended to avoid round tables because it was more difficult to partition them into individual workspaces as compared to square or rectangular tables (Thompson, 1973).

One method used to make these transitions fluid is to provide a separate personal display adjacent to the main tabletop computer display. The user can then easily shift her attention from the personal display to the group display with minimal effort. Separate displays also create obvious boundaries between the personal and shared workspaces, although as noted earlier, the separate displays may hamper interpersonal interaction. Collaborative environments such as INTERACTIVE WORKSPACES (Fox et al., 2000), AUGMENTED SURFACES (Rekimoto & Saitoh, 1999), and I-LAND (Streitz et al., 1999), provide mechanisms for secondary devices to be placed on or adjacent to the tabletop display. In the INTERACTIVE WORKSPACES and AUGMENTED SURFACES environments, participants are encouraged to use personal laptops that are linked to the tabletop display by underlying software architectures. In the I-LAND environment, participants can each use a personal CONNECTABLE (Tandler et al., 2001), which combine with others to form a larger group workspace, allowing users to transition easily from individual to group work.

In contrast to this hardware approach, partitioning the software tabletop display space is another way designers have provided distinct workspaces. The PDH system provides a unique method of providing users with distinct work area. Each corner of the tabletop display is designated as storage space for personal bookmarks while keeping the circular central area as a group space (Shen et al., 2002). PDH also provides each user with a system menu at the table edge, allowing them to access the system functionality without disrupting other users. These features allow users to attend to their own activities or the group activities without changing the entire display for each type of activity.

Partitioning the input space, or providing the ability to integrate personal computing devices is essential for supporting both personal and group spaces on the table. How to best support the transition between theses two spaces still needs to be determined.

Support Transitions between Tabletop Collaboration and External Work

Most collaborative tabletop activities are part of a larger group effort that exists beyond the tabletop environment. Co-located group interaction is only one part of daily collaborative activity (Luff et al, 1992), thus group members must be able to incorporate work generated externally to the system into the current tabletop activity. It is important for collaborative tabletop systems to allow users to easily transition between mutually focused work and independent work done beyond the tabletop environment (Elwart-Keys et al., 1990; Mandviwalla & Olfman 1994).

To ensure an easy transition between external work and tabletop collaboration, several systems support the use of off-the-shelf software (Fox et al., 2000). These systems allow participants to use previously generated files in the group setting. Transferring files either across a network or using storage devices is often more complicated and cumbersome than necessary. Transferring data from one display to another should be as simple as saying "I want this information displayed there" while gesturing to the appropriate data and display.

Several mechanisms exist to help facilitate importing and exporting of external work. Within the I-LAND environment, the PASSAGE mechanism allows users to easily move digital information from one computer to another (Streitz et al., 2002). Users associate digital information with any small object (e.g., a pen or key chain) by placing it on a 'bridge' associated uniquely with each computer in the environment. Moving the object to the INTERACTABLE bridge causes the digital information to appear on the tabletop. The hyperdragging technique developed for the INFOTABLE (Rekimoto & Saitoh., 1999) supports a seamless transfer of digital information between a table, wall display, and laptop computers. Hyperdragging simply uses normal mouse operations in combination with the physical relationship among the computers. The POINTRIGHT system (Johanson et al., 2002) in the Stanford IROOM (Fox et al., 2000) integrates displays on the table, wall and portable computers with a single set of mouse and keyboard controls. The CAFÉ TABLE (Kyffin, 2000), utilizes tagged objects, called tokens, which can be recognized by other computer systems in the users' environment, allowing for ease of data transfer.

Support the Use of Physical Objects

Tables are versatile work environments with a unique characteristic of providing a surface for people to place items during collaboration. These items often include both task-related objects (e.g., documents, notebooks, design plans) and non-task-related objects (e.g., beverages, day-timers, hat & gloves). Tabletop systems need to acknowledge these items as well as provide additional digital features. Studies have shown that paper persists in many work environments, even along-side computers that were meant to replace it, because of the versatility that paper provides (Luff et al., 1992). Providing technology that allows the seamless integration of digital and physical objects at the table will support the practice of bringing objects to the table mentioned above, allowing users to apply the years of experience they have accumulated collaborating around tables.

To support the practice of using physical objects on a table, researchers have begun offering tangible user interfaces (TUIs) as an alternative to standard computer input devices. Some systems use generic items, such as bricks, for generalized tangible input (Rauterberg et al., 1997; Fitzmaurice et al., 1999; Patten et al., 2000). Other tabletop systems provide specialized artifacts related to the application task. For example, the URP system uses pre-existing building models as input to an urban planning system (Underkoffler & Ishii, 1999), while the ENVISIONMENT AND DISCOVERY COLLABORATORY (EDC) (Arias et al., 1999) has tracked objects representing components of a neighbourhood (e.g. trees and buildings) for simulation and design tasks. The METADESK system handles physical objects by providing specialized tools for generic tasks (Ullmer & Ishii, 1997).

Instead of tagging objects, some current systems use computer vision technology allowing objects to retain their physical form and be used as intended, as well as be recognized by the system. Matrix codes were placed on objects such as textbooks (Koike et al., 2000) and videotapes (Rekimoto & Saitoh, 1999), which were captured and interpreted by overhead cameras. Radio frequency identification (RFID) tags were embedded in clear acrylic tiles by Rekimoto et al. (2001) to create modular graphical and physical interaction devices. The disadvantage of using tagging technology is that objects must be pre-tagged to be interpreted, limiting the possible system input. Instead, Wellner's DIGITALDESK (1993) can read and interpret information created with a standard marker on paper. The DESIGNER'S OUTPOST (Klemmer et al., 2000) captures and interprets regular Post-it Notes™ while PINGPONGPLUS (Ishii et al., 1999) augments the interaction between an unenhanced ping-pong ball and a ping-pong table. These three systems bring in physical artifacts, not previously enhanced by technology.

There are many digital or physical objects that users may want the system to recognize (e.g., laptop computer, daytimer, ping pong ball), but tabletop systems must allow users to interact with objects that are not interpreted by the system (e.g., coffee cups, notebooks). Using a robust surface such as the DIAMONDTOUCH display (Deitz & Leigh, 2001) encourages users to treat the system surface as a table, not as a delicate display. Systems using self-illuminating displays can be enhanced by providing a boundary around the display on which to place objects (Streitz et al., 1999; Fox et al., 2000). Finally, although a system may ignore a coffee cup placed on the table as input, there needs to be a mechanism that recognizes the placement of an object and does not display relevant information in the physical space occupied by the item.

Provide Shared Access to Physical and Digital Objects

Tables are an ideal environment for sharing information and objects with others. It is common to see work colleagues, schoolmates, and family members standing or sitting around a table discussing some object. For collaborative designers, sharing a work surface can enhance the design process (Bly, 1988). Furthermore, pointing or motioning to a shared object during a discussion occurs in the same spatial relationship to the object for both the gesturer and the other group members, facilitating the group communication (Bekker et al., 1995; Tang, 1991). In contrast, in situations where everyone has a copy of a digital object, a gesture made to one copy of the object forces the other group members to perform a spatial translation to determine the specified location on their own copies. This creates cognitive overhead to using important communicative tools such as gestures and deictic references (Bekker et al., 1995; Bly, 1988; Tang, 1991; Gutwin et al., 1996). Interacting with shared artifacts can also help maintain the group focus and facilitate awareness within the group because body positioning and eye gaze of group members attending to the same object can be easily interpreted by other group members (Suzuki & Kato, 1995).

Depending on the nature of the collaborative task, participants may be working primarily on a single object, such as one large design sketch, or they may be working on a series of related objects. Design tasks are a major application area where the sharing of common objects is essential. Arias et al. (1997, 1999), Underkoffler & Ishii (1999), Fjeld et al. (2000), and Eden et al. (2002) have built collaborative tabletop systems for urban planning. The collaborators typically gather around the design plan, and manipulate additional icons or physical pieces to add or delete design elements. Not only does a single representation of the design object ensure that each participant sees the same updated plan, but each participant can also see others place new elements as the actions happen. Furthermore, gestures can be easily interpreted during discussions. The shared object may be one large object such as a human skeleton (Cutler et al., 1997) or composed of several smaller pieces that comprise an organization scheme (Grant & Winograd, 2002).

When people are located at various positions around the table, the orientation of a shared object can become an issue. Orientation of an object can be both a problem and a potential resource for group interaction (Tang, 1991; Kruger & Carpendale, 2002). It may be difficult for one group member to read a document that is oriented toward the other side of the table, but collaborators often use temporary and partial rotation of objects for communicative purposes, such as directing the group's focus, sharing information, and assisting others (Kruger & Carpendale, 2002). Providing flexible, user-controlled orientation of shared objects on the table would facilitate this communicative function. Systems which support the maintenance of personal and group workspaces through appropriate orientation of objects towards the users around the table (e.g., Rekimoto & Saitoh, 1999; Tandler et al., 2001), partially provide this functionality. Different approaches to integrating orientation into a table interface are discussed in the next section.

Additionally, occlusion can be an obstacle to fluid interaction with a shared object. When using top-projected displays (e.g., Omojola et al., 2000, Patten et al., 2001; Rekimoto & Saitoh, 1999; Underkoffler & Ishii, 1999), one collaborator's hand can block the projection, obscuring the shared object for the other participants.

Consideration for the Appropriate Arrangements of Users

During tabletop collaboration, people sit or stand around a table at a variety of locations, both in relation to the table and in relation to other group members. Several factors can influence people's preferred locations, which in turn can influence the interpersonal interactions within the group (Sommer, 1969).

Physical properties of the table, such as size or shape, can influence seating positions. People generally have several distance zones at which they feel comfortable interacting with others (Hall, 1966).[2] Group members may temporarily be permitted to interact within a person's "intimate" space, but interaction at this distance for prolonged periods will often feel socially awkward. People generally feel comfortable working at "arm's length" since this preserves their personal space (Hall, 1966). Different cultures (Hall, 1974) and age groups (Aiello, 1987) are more comfortable interacting at closer distances than others. Young children tend to prefer closer interactions than adults (Aiello, 1987). Consequently, children tend to favour side-by-side or corner seating arrangements during tabletop activities compared to the face-to-face seating arrangement more commonly preferred by adults (Sommer, 1969).

The group task can also influence users' preferred locations at the table. Activities that require coordinated actions may best be supported by close user positions, because this positioning can enhance workspace awareness (Suzuki & Kato, 1995; Sommer, 1969). When the group activity is focused on conversation, adults generally prefer to sit in a face-to-face or corner seating arrangement (Sommer, 1969). Whether the collaboration is focused on communication or cooperative action can influence where people prefer to sit. Thus, the technology needs to be flexible enough to support users interacting from a variety of positions around the table.

Many current systems have cumbersome technology that renders one or more sides of the table unavailable to users (e.g., Wellner, 1993; MacKay, 1993; Culter et al., 1997). Other tables also incorporate a vertical display attached to one side of the table, which leaves only one side of the table with optimal viewing conditions (e.g. Rauterberg et al., 1997; Koike et al., 2000; Patten et al., 2001; Rekimoto, 2002). There are also table systems that provide vertical displays near the table without hindering the use of any sides the table (e.g., Arias et al., 1999; Fox et al., 2000).

When users are sitting at various locations around a table, the displayed information may not be oriented appropriately for all users. A non-oriented interface (e.g. Mandryk et al., 2002) would be appropriate for horizontal displays, but is unrealistic for work practices where rotation-sensitive components (Fitzmaurice et al., 1999) such as menus and text are present. As a result, providing support for orientation is a challenge and a salient issue for tabletop system research.

There are two main approaches to the orientation problem: having a system automatically present information in the best orientation and allowing users to manually rotate information themselves. The CONNECTABLES (Tandler et al., 2001) and INFOTABLE (Rekimoto & Saitoh, 1999) systems automatically orient

[2] Hall identified four distance zones: Intimate (touching – 18 inches), Personal (1.5 – 4 feet), Social (4 – 12 feet), and Public (+12 feet).

information towards a user while assuming that a user's position will be based on their static "personal" display space. This could potentially lead to inappropriately oriented objects if users move around the table. Hancock et al. (2001) used a neural net to predict the location where users were seated based on input from a tracked stylus input device so that information was automatically projected toward each user, even if the users moved around the table. Automatically orienting information allows for ease of reading and interaction with oriented components such as menus, but it limits the use of orientation as a communicative function, as discussed in the previous section. A hybrid approach where rotation-sensitive components would be automatically oriented and users could still control orientation for use as a communicative means might be more beneficial.

Support Simultaneous User Actions

When multiple people engage in tabletop activities, they often interact with artifacts on the table surface simultaneously (Tang, 1991; Scott et al., 2003). Traditional computer technology does not support multi-user, concurrent interaction. Instead, users are forced to share the available input device when working together at a single computer (Inkpen et al., 1995). This limitation still exists in large-screen displays used with many existing tabletop systems, sometimes interfering with users' actions during collaboration (Ståhl et al., 2002; Shen et al., 2002).

Teamwork is often comprised of a variety of collaboration styles, including working in parallel, working sequentially in tightly coupled activities, working independently,[3] and working under assumed roles, such as director and actor (Cockburn & Greenberg, 1995; Scott et al., 2003). On systems that don't provide support for concurrent interactions, users can adapt to technology limitations and learn to take turns (Shen et al., 2002). However users may have more difficulty working independently because they must monitor their collaborators to know when the system is available. Thus, providing concurrent interaction would free users to focus on the task at hand, allowing them to take advantage of these different interaction styles to suit the task requirements and the group dynamics (Mandviwalla & Offman, 1994; Scott et al., 2003). On collaborative systems where concurrency is not supported, users have requested the ability to interact simultaneously (Shen et al., 2002, Grant et al., 2003). In addition, when simultaneous input is provided, users have appreciated this feature (Hancock, 2001).

Providing concurrent, multi-user interaction is both a hardware and software consideration. The tabletop system must provide multi-user input capabilities, such as multiple input devices or touch screens that detect simultaneous, multiple

[3] When independent interaction is coordinated it is sometimes referred to as the divide-and-conquer collaboration style (Gutwin et al., 1996).

touches. The software must also support interacting with multiple software components at once. For example, single display groupware (Stewart et al., 1999) allows users to manipulate group widgets on a shared display and provides multiple, on-screen cursors. Tabletop systems that provide a tangible user interface must intelligently handle manipulation of multiple input objects at once.

Currently, only a few tabletop display systems support synchronous collaboration. The majority of current systems require turn-taking with only one input device and one active input channel (i.e. cursor) (e.g., Wellner, 1993; Fox et al., 2000; Scott et al., 2002). These systems may be collaborative in the sense that multiple people can gather around and discuss the digital information, but only one person can manipulate digital artifacts at any given time and control must be passed for a second user to interact. Providing each user with an input device, even though the system cannot interpret concurrent input, requires that users take turns but does not require the passing of control. This is the approach taken by the PDH system (Shen et al., 2002) and the ITABLE (Grant & Winograd, 2002) using ultrasonic pens, and is also inherent in any system that uses standard touch-sensitive screens (e.g. Streitz et al., 1999; Ståhl et al., 2002).

Recently, efforts have been made to create technologies that allow for multiple, concurrent interactions. DIAMONDTOUCH (Deitz & Leigh, 2001) enables multiple concurrent users as well as multiple simultaneous touches from a single user. SMARTSKIN (Rekimoto, 2002) uses similar technology that allows for multiple concurrent interactions as well as supporting gestural input. Many systems that use tangible user interfaces (TUIs) for specialized input can simultaneously track multiple physical tokens (e.g., Fitzmaurice et al., 1995; Patten et al., 2002; Eden et al., 2000; Mandryk et al., 2002); however, the latency of a system may increase as more tokens are manipulated concurrently.

There are many methods of providing multiple, concurrent input to a tabletop display system. Research is required to determine which input mechanism (e.g., mice, gestures, touch, stylus, or TUI) is the most beneficial under different collaborative situations. The speed and accuracy of various input devices has been well documented, but their impact on collaborative issues such as communication and awareness of activities has not. For example, collaborators are more likely to see another collaborator access an icon when using a touch sensitive display since their whole arm is moving in space than when using a mouse when only a small cursor moves. This increased awareness may be worth a small decrease in speed of interaction in certain collaborative circumstances.

Directions for Future Research

Current tabletop systems satisfy to different degrees the eight system guidelines presented. However, as a research community we need to make progress in several directions in order for our field to further support effective collaboration.

These research directions include the standardization of methods to evaluate co-located collaboration, the implementation of more comparative studies to understand the impact of system configurations, and the creation of a taxonomy of collaborative tasks suitable for tabletop collaboration.

Our guidelines should be useful signposts for tabletop system and interface designers to use when considering important collaboration support issues. However, we also need further development of a robust evaluation methodology. Recently, attempts have been made to use conversational analysis as a measure of collaboration. Gale (1998) used the Conversation Games Analysis (Carletta et al., 1997) to determine the effectiveness of various collaborative settings for a remote repair task involving an expert and a trainee. The effectiveness of the COGNOTOR system to support co-located brainstorming was evaluated using research theories from Psycholinguistics, which helped reveal that the underlying conversational model that the system supported did not match the conversational model that people use when talking in a co-located situation (Tatar et al., 1991).

Evaluating collaboration on digital tabletop systems could benefit from comparisons to a control condition involving traditional media. Although there may be some limitations to this control setting, such as resizing or replicating information, studies based on traditional tabletop collaboration have provided applicable lessons for CSCW in the past (Bly, 1988; Tang, 1991; Grant et al., 2003).

Further work is needed as well to understand the suitability of configurations for tabletop systems before a single set of standard configurations are adopted by default. Each decision on system configuration affects the usability of a tabletop display system in a number of ways. For example, decisions about the size and resolution affect how many collaborators can gather around a table. Projection technology (e.g., top-projected, bottom-projected, self-illuminating) affects the viewing angle, brightness, and robustness of the system but also influences interaction. In addition to influencing individual interactions, decisions on input technologies and tracking technologies influence how well a system provides support for collaborative activities.

Moreover, the fundamental issue of when and whether a computer tabletop is the best display configuration for a task and user group needs further research. For instance, collaboration involving several people discussing textual information intuitively does not seem appropriate for a tabletop environment because of possible orientation issues, but research has suggested that orientation of tabletop items plays a key communicative role (Kruger & Carpendale, 1991). Thus, further investigation into the tradeoffs of using various types of information on the table (e.g. orientation-dependent versus non-orientation-dependent) is needed. We need the creation of a taxonomy of collaborative tasks to help determine which activities and tasks are better suited to a tabletop environment and why.

Conclusions

Based on an investigation of the current state-of-the-art in digital tabletop displays and our experience building tabletop systems and applications, we have presented eight guidelines for designing collaborative tabletop display systems. These guidelines are:

(1) Support interpersonal interaction
(2) Support fluid transitions between activities on the table
(3) Support transitions between personal and group work during tabletop collaboration
(4) Support transitions between tabletop collaboration and external work
(5) Support the use of physical objects on the table
(6) Provide shared access to physical and digital objects
(7) Consideration for the appropriate arrangement of users
(8) Support simultaneous user actions

These guidelines are grounded in research on communication and collaboration and will inform future designers of tabletop technology. For each guideline, we have described how current tabletop display systems either succeed or fall short of supporting the guidelines established. We have also presented specific information regarding how designers can build support for the guidelines into their systems.

In some cases, small changes in system design can result in large changes in the ability of a system to support collaboration. In other instances, there are research questions that need to be investigated and obstacles to overcome. We have presented a number of these obstacles and research directions identified from own work, our critical analysis of current state of the digital tabletop research, and discussions with other designers at a recent international tabletop workshop.

This paper presents the current state of tabletop display systems and applications as well as guidance for future research directions. We anticipate that this field will continue to develop and impact not only our research community, but also provide insight into human-computer interaction as a whole.

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