What Do You Bring To the Table? Investigations of a Collaborative Workspace

Trevor Pering, Kent Lyons, Roy Want, Mary Murphy-Hoye
Intel
{trevor.pering, kent.lyons, roy.want, mary.c.murphy-hoye}@intel.com

Mark Baloga, Paul Noll, Joe Branc, Nicolas De Benoist
Steelcase
{mbaloga, pnoll, jbranc, nbenoist}@steelcase.com

ABSTRACT
Collaborative spaces supporting personal mobile devices provide for a powerful integration of personalized content with supportive embedded infrastructure. Social, spatial, and informational considerations have a salient impact on such modern collaborative spaces. The design, implementation, and evaluation of a collaborative workspace prototype that directly supports the integrated use of mobile devices not only yields insights into the basic capabilities behind such a space, but also a deeper understanding of the different composition control mechanisms available. Specifically, such environments can effectively work with existing laptop platforms, and show increased promise for supporting future generations of smaller mobile devices.

Author Keywords
Collaboration, mobile computing, shared workspace, ad-hoc configuration, platform composition.

ACM Classification Keywords
H5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

General Terms
Design, Experimentation, Human Factors.

INTRODUCTION
The introduction of highly capable mobile computers into workplace environments has altered the way knowledge workers conduct their work. For many individuals and companies, the mass adoption of laptops and high-speed networking technologies has expanded the choices people have in deciding where to work. For example, not only have modern coffee shops become popular destinations for conducting work, but some corporations are altering their internal spaces to support work environments that resemble those coffee shops.

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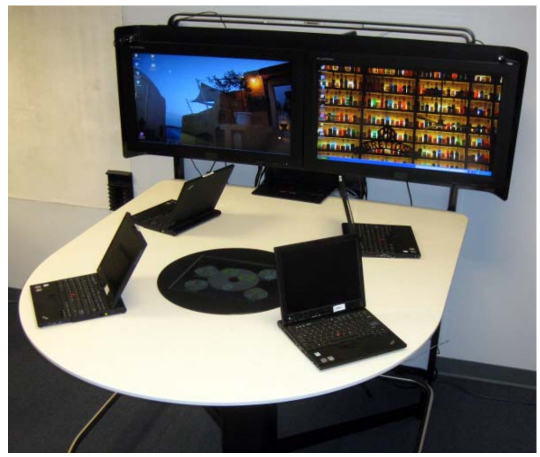

Figure 1: A collaborative workspace table prototype, showing four laptops, two embedded displays, and a central embedded control surface.

Even in many traditional work spaces, coworkers will routinely bring a laptop or smartphone device to meetings, and use them either to interact with their colleagues (projecting, sending email, looking up information) or to multitask with personal activities. As mobile devices become smaller and more capable, the dynamics of these situations change with smaller devices becoming more prevalent and more personal but less immediately useful for traditionally intensive work, such as creating documents.

Advancing mobile device technologies provides the basis for integrated collaborative systems that combine personal familiarity with shared spaces. Even in today's work environment, personal mobile devices often form the basis for shared experiences through a laptop connected to a projector by a VGA cable. Studies of specific collaborative applications such as gaming [23], photo-sharing [2], and general file-sharing [28], detail how mobile platforms can enable new collocated experiences for specific applications. However, many of these experiences could benefit from a more flexible collaboration capability than is provided by existing environments: the underlying needs are evident, but the overhead required to connect technologies together, or switch between them, is prohibitive.

The collaborative workspace prototype shown in Figure 1 is designed to support knowledge work on mobile platforms and complement it with local infrastructure resources in support of transparent collaboration. The core system focuses on the confluence of *in situ* mobile devices that are networked with two shared displays fixed in a collaborative table and an embedded display and control surface at the table's center. The impact of bringing mobile devices together with an interactive workspace is explored through a user study that evaluates several four person groups each collaboratively performing a generative design task.

The core hypothesis is that embedded computing and an integrated interface will be complemented by mobile computing resources brought to the table to create an enhanced collaborative workspace. This work highlights three main contributions:

1. A prototype physical workspace with integrated computation, supporting flexible display sharing, centralized storage, and an embedded control surface.
2. A dynamic composition capability supporting sharing among mobile devices and the workspace environment for *generative* collaboration.
3. Findings from a user study covering the collaborative use of embedded and mobile components, focusing on controlling the connections between devices.

WORKSPACE TRENDS

Work today is often multi-disciplinary and multi-organizational, and requires complex coordination to manage potential innovation [6]. The core motivation for creating enhanced collaborative spaces stems from a solid understanding of the nature of group work and the technological trends of mobile computing – leading towards systems that are more suitable for *generative* work, in addition to the fundamental actions of cooperation-oriented *choosing*, *negotiation*, or *execution* tasks [17]. A more accessible and flexible work environment can improve business processes, reduce reconfiguration costs/overhead, and utilize space more efficiently. Given the confluence of collaborative needs, mobile technologies, and generative work, developing these spaces requires design principles that balance social, spatial, and informational factors.

Workplace Collaboration

While the technology and physical work environment may be changing for knowledge workers, the nature of that work retains collaboration as an essential component because knowledge work is primarily a social activity. Though knowledge workers do spend some time working alone, the business of creating, evaluating, and disseminating knowledge is in large part a shared enterprise. Workers share news and information with others, form new concepts, bounce ideas off of each other, discuss and consider different options, make decisions, and follow through with other activities as a team.

Collaboration expedites knowledge work for several related reasons:

- Business problems are more and more represented as complex "wicked problems" [3], and solving them is a fundamentally social problem.
- Working collaboratively breaks down silos in an organization, improves communication, and speeds the work [9].
- The generative nature of knowledge work lends itself to interaction, discussion, and collaboration [4].

Towards these ends, the social considerations of workspace designs are crucial, motivating the core design and evaluation of the proposed collaborative workspace prototype.

Trends in Mobile Computing

Unlike the social aspect of collaborative work, technological capabilities are changing at a staggering rate. The oft-quoted Moore's law, which predicts a doubling of the number of transistors per unit area in microprocessors every two years, has held true and similar trends are seen with storage and communication technologies for mobile devices [24]. These trends have lead to the explosive adoption of highly-capable personal computers. Laptops are now the dominant computing platform for individuals. Likewise there are tremendous opportunities provided by smaller mobile devices such as netbooks and computationally powerful smart phones, such as the iPhone. The key aspect of all these systems is *mobility*, essentially enabling them to be always present and integrated with a user's activities throughout the day.

Although many capabilities of mobile technologies have been improving at a dramatic rate, the overall user interface affordances are fundamentally limited since they are largely defined by the physical size of the device. One potential solution to this conundrum is the utilization of infrastructure-based computing to support mobile capabilities [29]. The current generation of the mobile workforce still utilizes fully-capable mobile devices typified by the laptop computer; however, popular trends in information technology systems point towards an increased reliance on smaller and smaller devices. Accordingly, emerging workspaces should support spatial accommodation for a variety of mobile devices, with an eye towards shrinking interface capabilities.

Generative Knowledge

Evolving products, services, and spaces are creating new behaviors and increasing the value of digital information for users [16]. Current configuration of traditional shared-spaces reinforce a singular approach to the sharing of ideas: presenting polished slide-decks of pre-generated information. Although this model *indirectly* supports collaboration either through verbal discussion or technologies such as email, it imposes a fairly strict structure on collaborative participants since one person is rigidly identified as the "presenter." For example, a standard presentation environment makes it very hard for a participant to quickly show the group a picture to invoke a creative conversation.

Generative knowledge work, therefore, can benefit from a more free-form interaction among participants, enabled by more fluid information exchange between components [1]. Furthermore, it can be beneficial to extend sharing to a wide variety of resource types including storage [28] and other non-visual resources, effectively broadening the capabilities of the information channels. Knowledge workers are in fact characterized by diverse and uncategorized handling of information [16], a characteristic that should therefore be supported by the underlying information technology. The dynamics surrounding generative knowledge work suggest that systems be dynamic and flexible in the ways they support information sharing.

Collaborative Workspace Design Principles

The social, spatial, and informational factors suggest three corresponding design principles that have influenced the design of the collaborative workspace prototype:

- *Social*: Provide equal access to information to build on ideas, create a shared focus and empower workers to make timely, strategic, and informed decisions.
- *Spatial*: Support a variety of personal mobile devices and accommodate their interaction within embedded components.
- *Informational*: Enable flexible information sharing by making content visible, accessible, and editable to those that most need it.

The prototype workspace directly embodies all these design principles, while the corresponding evaluation focuses on the considerations around the spatial aspects of incorporating mobile devices into the workflow.

RELATED WORK

Based on the architectural configuration of the underlying elements, salient related work can be divided into three sections: collaborative spaces, tabletop systems, and mobile capabilities. A collaborative space is loosely termed something you work *within*, while a tabletop is something you *gather around*, each providing a fundamentally different focus of social attention. Further, in contrast, mobile systems are designed to meet the needs of distributed mobile professionals or social groups, enabling people to collaborate *independent* of location.

Previous work has shown that personal computers combined with infrastructural support increases the quality of collaboration [1][21][27], but it remains an open question as to *how mobile devices* should be integrated with fixed infrastructure, an staunch evolution from the very first exemplars of interactive environments [25].

Work on collaborative spaces has typically focused on middleware solutions that support collaborative applications [15][26]30][12] or only screen sharing. Middleware creates highly flexible environments at the cost of requiring custom applications targeting that space or restricting sharing to data, while screen-only systems don't enable sharing documents, I/O devices, or remote-control among devices. Furthermore, previous research carried out on these systems does not directly evaluate the underlying mechanisms for integrating the mobile devices into the collaborative space: now a primary consideration given the prominence of mobile devices, and mobile work practices in a modern enterprise environment.

Tabletop systems provide a different model of collaboration where a single resource, the table, is the central component of the interaction. Integrating mobile devices with a table typically has been focused around custom applications that allow the sharing of media, documents and game components [14][23][22], which enable mobile devices to share content with the table, but then focus on the table surface itself as the primary means of collaboration. In contrast, the prototype described in this paper treats the shared table as a peer among the devices, increasing the flexibility of sharing options – at the expense of a less interactive surface.

Collections of mobile devices provide a powerful construct for collaborative systems [11][20] and generally represent significant management challenges for a user [7][19]. Furthermore, there are many standard systems that are designed to support collaboration in a modern workforce [8][10], which is often highly mobile and distributed in structure, but these solutions currently remain independent of collaborative spaces.

COLLABORATIVE WORKSPACE

As personal office spaces continue to decline in either size or dedicated assignment, corporations are migrating towards more and varied shared spaces for those individuals deciding to work on campus. Understanding how dedicated project rooms, and assigned meeting spaces for group work can be used to advantage is a subject of research [18]. Resources inside either shared, or dedicated group workspace, vary considerably from minimal sets of ergonomic comforts to rich sets of emplaced analogue tools and devices. Embedded computation and interaction elements have the potential to evolve contemporary workspace designs with the goal of supporting advanced knowledge work.

Contemporary Workspace

The workspace prototype developed for this paper is based on the Steelcase media:scape design[1], which is an assembly of furniture primarily consisting of a conference table (54"w x 63"d) in the plan view shape of a D. Suitable for several people, the table is elevated 39.5" from the floor. The attached upright totem positions two 32" monitors, side by side, at one end of the table. In the table's center is a 17" touch display held in a round bezel. The center of this surface-interface is reachable within 27" from the table's edge.

Different than traditional conference rooms, the original media:scape design provides each user with a VGA cable integrated with physical switch that can be used to share content from their laptop display through a video switch embedded below the table. The physical switch has two basic functions: Pressing it to put personal content on a display, or pressing to disconnect and remove personal content from display. Additionally, an illuminated indicator on each switch shows whose laptop content is on public display. These switches are replaced by the touch display in the center of the prototype system.

This level of persistent, instantaneous access permits participants a new-found freedom to contribute uniquely held information [5] into the dynamic flow of information. In an engaging meeting, where displayed information is flowing freely between individuals, knowing whose information is on display and who is gesturing to present new content are non-verbal signals that a visible, tangible interface can both reflect and assert by its design and position.

The socialization of known and discovered information affords embellishment, comparison, extension and debate for more informed content creation or decision making. Assembling this combination of social, spatial, and informational resources conceptually helps a group excel through enriched implicit communication and awareness [13] and is foundational for today's search-enabled collaborative interactions.

Embedding Computation

The collaborative prototype embeds three computers in the existing design. There is one computer driving each of the two upright displays. Additionally there is a computer providing storage and clipboard resources common to the workspace, and drives the interactive surface, described in the next section. In contrast, the commercial media:scape design only provides support for connecting the user's laptops to the integrated displays through a VGA switch, but does not provide any computational support. Each embedded computer is a Dell Optiplex 160 with an Intel Atom 330 running at 1.6 GHz and 2 GB of DRAM.

[1] http://www.steelcase.com/na/media_scape_products.aspx?f=38450

There are several opportunities enabled by providing embedded computational support:

- A dedicated computer driving each display means that a person does not need to give up control of their own computer to show content to the group. For example, by remotely controlling an embedded display, a user can maintain the privacy of any information on their desktops (such as side-channel chat conversations).
- Centralized storage provides a file-share that is independent of any of the devices the users bring to the space. This can be exercised in multiple ways but logically provides a storage location for any digital information used by the group during active collaboration.
- Embedded computation provides support for smaller form-factor devices, such as smartphones, since these devices can provide personal content capability but are fundamentally limited in their interaction affordances, power profiles, and computational capabilities.

Control Surface

Composition control for the workspace prototype is provided through a touch-screen display centralized on the surface of the table. This centralized display is similar to many "table top" systems that enable shared interaction around a horizontal touch-oriented surface. However, by design, it is intended simply to control the connections among mobile devices and table elements, and is not intended as a direct collaborative resource. In the workspace prototype, the surface runs a composition middleware program described in the following section.

The integration of the interactive control surface is designed to support several basic capabilities within the workspace. Similar to the physical control elements of the commercial design that it replaces, the central surface permits shared visibility to all participants. Additionally, this allows "at-a-glance" comprehension of the shared resources for navigation and contribution. The central location of the control surface allows participants equal access to all devices and connections, allowing a "democratization" of management of display, sharing, and content creation. Finally, the "shared" tangible reach into the communal control surface heightens the co-realization of the collaborative session.

EMBEDDED COMPOSITION

Integrating users' mobile devices with the physical workspace is accomplished using a modified version of Platform Composition [20]. Specifically, the underlying system was modified to directly reflect the physical configuration of the embedded computing components (two screens and central storage). The overall digital architecture of the system is shown in Figure 2. The middleware layer is implemented in Java and runs on both Windows, Linux, and Macintosh platforms; the specific instantiation for this design relied on a mix of Windows XP and Windows 7

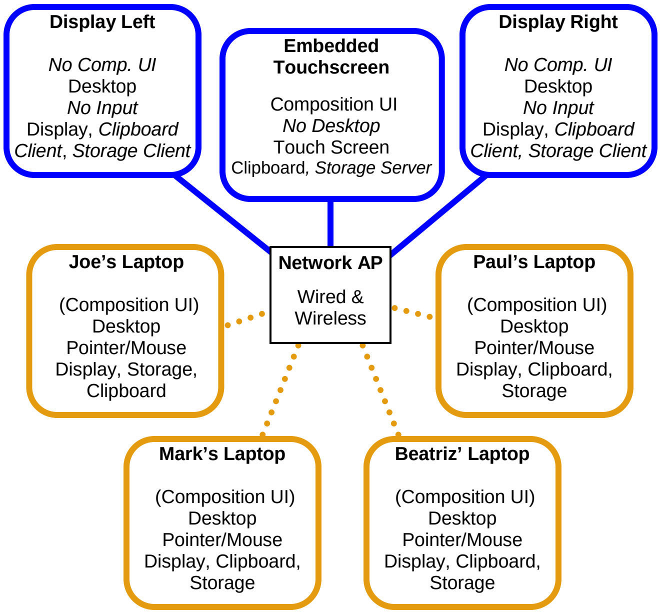

Figure 2: Logical Framework of the composition system, showing three embedded computers and four (identical) user laptops. Items in *italics* deviate in a salient way from others in the group, and "( )" indicate optional components (e.g., an iconified window). Services are client and server unless otherwise specified.

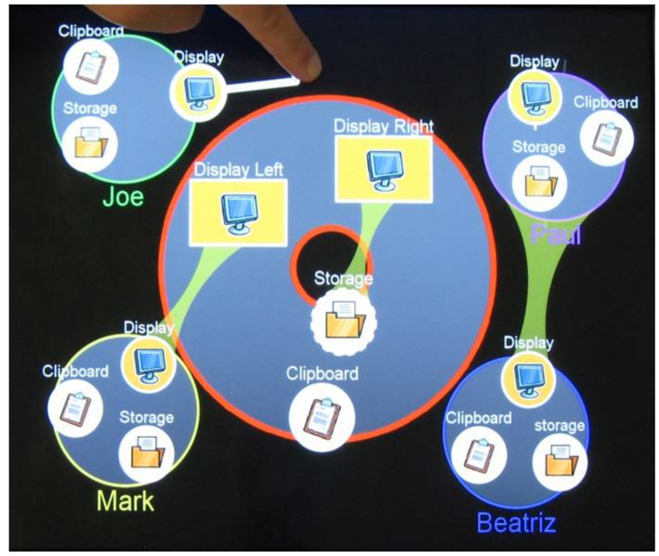

Figure 3: Graphical interface showing the embodiment of the logical architecture in Figure 4. A "join-the-dots" metaphor is used to create compositions by joining servers (small circles) with client (large circles). Resources associated with the three table platforms (Display Left/Right and Storage/Clipboard) are floating in the center, not visually associated with a specific computer.

systems. By design, Platform Composition supports any standard desktop application (such as MS Word, PowerPoint, Firefox, or Photoshop), a capability that is a functional requirement in many workplace environments.

Platform Composition represents but one of many possible resource sharing middleware layers that could be used to facilitate the integration between fixed and mobile systems [8][11][14][15]. The primary contributions of the prototype system focus on bridging the divide between mobile and fixed systems in a cohesive and coherent collaborative system, not the underlying sharing mechanism. There were three key changes made over the underlying Platform Composition system in order to adapt the core system to the workspace environment: embedded computing integration, physical representation of the workspace, and the representation of shared table resources.

Embedded Integration

In order to scope and limit the systems' information architecture, the collaborative workspace environment hosts a dedicated access point isolated using NAT from any external network. Once connected with the access point, all the devices automatically discover each other using standard network discovery protocols.

Use of NAT allows devices to access external content (email servers, web pages, etc…), but provides scoping for who is involved with the collaborative activities. E.g., defining who could access the centralized shared storage. This networking and security solution meets the minimum standards for a functional prototype, but are not intended to be research contributions, nor necessarily sufficient for production environments.

Physical Manifestation

This composition graphical user interface, depicted in Figure 3, provides a representational, interactive graphic showing an abstract representation of the physical table, vertical displays, users' mobile devices, and all available shared resources. The presented interface is the same on the laptops and embedded screen, except that on the laptop it is presented in a (possibly hidden) stand-alone window, while it is exclusively full-screen on the embedded display.

Personal mobile devices appear spatially oriented to reflect the physical position of the seated user, although currently the physical position is determined *a priori* (users were not allowed to move during the experiment). Refer to the Future Work section for a more complete discussion of this topic.

Although touch interaction is in a sense tangible, the prototype system differs significantly from the commercial media:scape system in that it does *not* present a physical embodiment of control between mobile devices and the embedded systems. Rather, it relies on a more complex display which has the potential to offer more status and interaction capabilities, at the expense of potentially overwhelming the user.

Embedded Resources

Resource connections are made through a simple line drawing metaphor between core resources (e.g., their display) and a target system (collaborator's laptop). In addition to the core peer-to-peer resource sharing capabilities [20], resource sharing is possible with the table systems:

- *Display Sharing* can be used to share a laptop's screen with one of the vertical displays or control them remotely, in addition to peer-to-peer sharing with laptops. It is not possible to share to/from the central touch screen display, since it is by design relegated to control of sharing itself.
- *Storage sharing* can be used to access the storage server in the center of the table, although a system's storage *can not* be shared to the table. Conversely, storage *can* be shared to either of the vertical displays, although the displays themselves do not provide any accessible storage. Storage can be shared from the central storage to either vertical display.
- *Clipboard sharing* can be directed at either vertical display, and can be shared through the central table, if desired. Although clipboard sharing is also provided as part of the display sharing solution, this implementation allows one person to place something on their clipboard and another to consume it *without* also sharing a display.
- *Peripheral sharing* enables users to share external peripherals associated with the table with mobile devices. This is not a key factor for larger devices such as laptops, but is a critical capability for smartphones and other small devices. The evaluative experiment did not allow peripheral sharing, although it is part of the core system.

PROTOTYPE EVALUATION

Our evaluation focuses on how groups of participants use the collaborative work space in conjunction with their individual laptops. During the evaluation, each group was tasked with producing a document out of resources that were distributed amongst their individual computers. The experiment consisted of three phases. The first phase was a practice session, and the last two phases were experimental trials.

Each participant was provided with a Lenovo X61 Laptop PC running Windows 7 and sat at the collaborative workspace as described previously. Each system was pre-seeded with a set of images and text for the experiments, as described below.

Participants

Sixteen participants in four groups of four were recruited from our organization by word of mouth: six women, and the median age of the participants was in the 26-35 rage, with three less than 26, and two greater than 35. They had previously known each other for a median of 1-2 years, with a few pairs having just met and one pair having known each other for more than 9 years. All of the participants were experienced computer users, and used laptops as their primary computer for work.

None of the participants had any previous experience with our system. Each participant was compensated with a $50 gift card for a single session, which lasted less than two hours. Furthermore, there were prizes of $50 per group member for the best document of each task (see below).

Practice Phase

During practice, a researcher explained the collaborative workspace and provided ample opportunity for participants to use and explore the system. Each participant was instructed to make and break links for the various services in different directions both between individual laptops and the table's embedded computers as well as directly between laptops. The instructions were given so that participants had the opportunity to utilize the sharing resources in a manner that could be used to complete the experimental task.

Given the flexible nature of the task, several examples were provided for accomplishing the same end-result by using different composition configurations (e.g. using storage vs. clipboard sharing, or editing a document on one of the laptops vs. on one of the table's displays). Participants were trained on either the laptop user interface, or the tabletop interface, whichever was used during the first condition of the experiment (see below). The practice portion of the experiment lasted approximately 30 to 60 minutes.

Task Specification

During each of two experimental trials, the participants were asked to perform a design exercise, which involved filling in a template with pictures and text phrases that were distributed across all four of their individual laptops. Each group performed two different design exercises, one on each interface (counterbalanced across groups).

The goal of the design framing was to simulate a scenario where each individual had previously accrued a set of resources (e.g. from performing web searches) and later they come together to collaboratively review and create a final document from that material. The first design was to create a set of images chosen from { building, fountain, landscaping, furniture } to specify the style of a new office building, and the second was to select food items for a holiday office party menu with sets { appetizer, pasta, entrée, desert }. Each laptop contained images for two sets from each task (e.g., { building, fountain, appetizer, desert }), and each set was distributed across two laptops. Therefore, participants had to collaborate in order to fully consider all potential images.

Additionally, each participant was furnished with a generic set of descriptive text phrases that could be applied to describe or explain their building or menu choices. Because the text was pre-defined, there was no need for participants to directly use their laptop keyboards or create new text.

The resulting documents for each category were judged by an anonymous and independent panel of four people based on the criteria provided in the template. Each participant in the team with the highest rated final documents for each category was awarded an additional $50 gift certificate.

Experimental Design

Each group of participants performed both tasks (with the order counterbalanced across groups), and they were allowed 15 minutes for each exercise. After each timed trial, the participants individually filled out a questionnaire and participated in a short focus group discussion. The questionnaire asked four Likert scale questions asking 1) if they could contribute to the task, 2) control the system's connections, 3) understand component connections, and 4) follow who was altering the composition.

Between trials participants switched the interface used to control the composition and were provided minimal instruction making sure they could operate it on the different hardware. After the conclusion of both trials, an exit questionnaire was completed to elicit pros and cons of our two conditions, and a semi-structured interview was conducted.

STUDY FINDINGS

All of the participants were able to use the system to work on the tasks during the trials, indicating that the participants were able to use both of our composition interfaces with the workspace system. Even though there were a total of seven computers to manage and numerous services resulting in a very large state space, the participants rapidly demonstrated that they understood the various components and could effectively connect and use the shared resources.

Given the time pressure of the design experiments, users had trouble with a number of basic aspects of the core system. Primarily, they had trouble with clipboard sharing due to a variety of reasons (e.g., problems with unfamiliar Windows 7 interface, conceptual misunderstanding, etc…). Also, they didn't understand some of the limitations of the display sharing system, such as the latency discrepancy between local vs. remote scrolling. The touch screen interface presented initial difficulties with pressure and parallax, but users quickly adapted to them and they did not present a significant issue.

Collaboration Strategies

Across all of the trials, participants adopted a number of different strategies for composing the various resources together and in how those resources were used to accomplish their document generation tasks.

Social Roles

The dynamic support provided by the workspace was evident in the roles participants adopted and transitioned between during the experiment. The collaboration during the experiment was very fluid even for the cases where the composition of system resources remained relatively static. The groups were very proficient at using the workspace to shift between individual work, work involving a subset of the participants, and work which required attention from the whole group. As the participants progressed through their tasks we saw very fluid shifts between these roles.

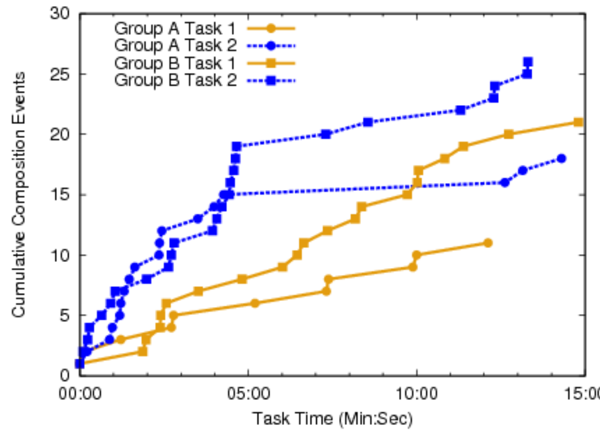

Figure 4: Cumulative Composition Events by Task Time for two groups, both tasks. A difference in the composition timeline can be seen between the first and second tasks performed by each group. Task 1 exhibits a more consistent slope, while Task 2 exhibits a steeper slope initially with a flatter intermediate plateau followed by a few trailing composition events, reflecting a change in composition patterns over time.

The roles participants adopted were also key to how participants understood and reasoned about the service connections in place at any given time. While the user interface did provide a mechanism for reviewing the currently connected services, during the course of the experiment, the participants seemed much more likely to think about the connections in place based on individuals. Many participants would ask questions such as "who has the left display?" or "who is editing the document?" to which the person actively using the resource would verbally respond. This type of reasoning was also used implicitly based on roles as they developed. For example, one participant commented that they knew that a certain person was responsible for performing part of their overall task and therefore knew that the underlying services had already been connected to share information with that individual.

Composition Strategies

There were also patterns that emerged in how the participants used the composition system as a whole. As can be seen in Figure 4, during some trials participants made and broke connections as they explored their individual resources and assembled the document. Another strategy was to form many connections near the beginning of the trial, and then to use that relatively static configuration to complete their task. For the former, the participants might swap who was controlling the displays to show each category of image, or use the clipboard to pass along information one piece at a time as the document was created. For the latter, often a form of star topology was formed so all of the participants could pass around information.

Specifically, several groups started by everybody connecting to the central storage and placing all of the documents on the central storage, and one group connected the clipboards of several of the computers together to create a common clipboard across all systems. Both of these strategies seemed effective for completing the task at hand.

Information Strategies

For several trials, there was heavy reliance on the central storage provided by the workspace. Some participants used it as a staging ground pooling *all* of their resources together during the beginning of the task. On the other extreme, several designs were completed holding only the working design document in central storage.

Participants used the workspace displays in both "projection" push and "remote control" pull modes. These different configurations have different implications for the latency of updating the display over the network, and groups explored both mechanisms over the course of the study. For most groups, both of these modes resulted in the shared displays being central to much of the group discussions and work. They were used throughout the tasks either for reference or as points for having a discussion.

There was one interesting exception in which a group adopted a different role for the shared displays during one of the tasks. In this example, the majority of the work was performed on the individual laptops with the large displays mostly being ignored. However, periodically an individual would show something on one of the shared displays, and call the group's attention to it to build consensus. After doing so, attention would then shift back to the laptops.

Clipboard sharing was more varied. One group used it very little, instead preferring to pass around documents using storage sharing across the devices. At the opposite extreme, one group used it almost exclusively for compiling their document. Other groups adopted a hybrid approach and would only use clipboard sharing for the text, or at specific phases during the collaborative task.

Composition Interface Affordances

Each participant had experience with both the laptop and embedded composition interfaces, giving them insight into the advantages and disadvantages of each. While, as mentioned above, the quantitative results did not show any statistically significant differences between the two, the qualitative data provided several interesting insights into the salient aspects of each interface.

Laptop Interface

Having the interface on the laptop provides several affordances. First, it leverages the traditional window interface paradigm. Participants could manage the composition interface window just as they do any other window running on their system, for instance using "ALT-TAB" to switch to and from the interface as needed.

The ability to easily hide the interface also provided some unexpected advantages. One user explicitly commented that hiding the *source* of information was at times a nice feature. Instead, they were more concerned with performing their work and getting the right information at the right time: If someone else was managing the connections, they did not need to know the details right at that moment.

Finally, some participants appreciated the individual control afforded by having the interface on each laptop. Each participant could make and break links (usually involving their own computer) without needing to wait on other users.

In a few situations, participants had trouble utilizing the composition interface on their laptop systems and did not ask for help, instead preferring to either repeatedly try an impossible operation (such as directly connecting their device's storage to the central storage) until they gave up and tried something else. This behavior points to the *personal* nature of personal devices, and highlights the more supportive learning environment of the embedded interface.

Embedded Interface

The embedded control interface on the table provided several complementary features. As expected, some participants appreciated the common display provided by the embedded control surface. They appreciated being able to see others making and breaking connections by reaching out into the center of the table. Some participants commented that the laptop screens interfered with their ability to easily reach in and interact with the embedded interface.

A side effect of having one interface that all four participants could see and control was that there was less uncertainty about the state of the system. The participants indicated that they were less certain everyone was seeing the same configuration when they were running the user interface from each laptop relative to the table interface.

The table also provided a mechanism for talking specifically about the connections in the system. A participant might comment about a link, or ask a question and point to the embedded UI. Likewise, others could follow along as a participant was making a connection, and these users could see the whole sequence of connections being made that led to a resulting composition. In contrast, the laptop only shows connections after they are successfully formed, resulting in a delay between a user action and the realization the system had changed

Finally, the table interface provided some affordances for learning to use the composition system. Participants could see and ask questions of others, demonstrate specific examples, take over control of the interface as needed, and spot likely problems before they occurred. When using the interface on the laptop, these processes were much more opaque and had to be verbally negotiated.

DISCUSSION

The data from our experiment provide interesting insights into the augmentations we have built into our prototype collaborative workspace. The table's embedded computation provided a natural way to organize the collaborative work, and fully supported integration with user's mobile devices. The table provided resources common to all, but owned by no one. Without the embedded computing, an individual would need to dedicate resources from their own computer to host the group's collaboration. Instead, the workspace provided natural points for collaboration and the embedded components were truly treated as group resources.

There are three main aspects of the system that merit further discussion, again revolving around social, spatial, and informational aspects of the system.

Benefits of Social Control

The role of the composition control surface proved to be relatively subtle and nuanced. In directly comparing the use of the touch-screen interface embedded in the table to the graphical interface running on each user's laptop, our data show that our participants were able to use both effectively. It also showed that they could transition between them without incident, and that experience with one directly translated to using the other.

Most likely, transitional collaborative spaces will be less familiar to users than their ever-present personal mobile devices. Correspondingly, users are more likely to make errors or suffer from misconfiguration issues involving the space itself. Therefore, the more socially learnable aspect of the embedded space is attractive in that sporadic users will more likely receive help with composition-oriented problems. Principally, this leads to a correspondence between the collaborative system and social interface based purely on management and support grounds, actual collaboration notwithstanding.

Spatial Mobile Evolution

The joint use of computation embedded into the workspace table in combination with the users' own laptops proved to be very effective during the study. The sharing of services through composition proved to be a powerful and flexible mechanism employed by the participants to collaborate using both their individual resources as well as the embedded components provided by the workspace. Not only were services from the various laptops utilized, but all of the embedded resources were used by all of the groups at various points during the tasks, and in a variety of ways.

In the future, the true benefit of the table-integrated composition control surface is likely to become more important with the continued evolution of small, high-performance computers such as netbooks and smartphones. These smaller devices will likely have much more constrained user interfaces and the large dedicated space for controlling the composition provided by the table might become even more critical. Likewise the workspace can provide users with I/O peripherals to facilitate interacting with the small form-factor mobile devices.

Generative Information

Given our prototypes basis in the media:scape product, the heavy use of the shared displays was anticipated. However their use went beyond being passive mirrors of an individual's computer, and the more advanced bi-directional screen sharing capabilities were heavily utilized, highlighting the positive impact on generative work. The importance of the central storage was new capability added to this workspace, and very rapidly became an invaluable tool for many of the groups.

One improvement of the clipboard sharing capability that was suggested by one group was a more directed clipboard sharing interface. Functionally, these users preferred to think of "clipboard sharing" as sending a message directly to another participant: they essentially wanted to cut and paste directly *to* somebody, rather that a generic broadcast medium requiring more explicit coordination. This change essentially leverages the familiar chat paradigm, while still supporting tight integration with existing clients.

FUTURE WORK & CONCLUSION

One area for future work with this system would be to explore the longer term use of the system, mitigating any learning effects. Essentially, the question is, over time, what aspects of integration between the mobile devices and embedded compute infrastructure become most useful. Similarly, further investigation into the impact of smaller mobile devices on the system would be worthwhile, to better understand issues likely to be encountered by future generations of knowledge workers.

From a technological perspective, issues surrounding better proximity and security mechanisms would be worth investigating. Currently, the prototype relies on the wireless access point for both proximity detection (who is connected to the system) and security. Investigating and integrating mobile device positioning technology could potentially address both these areas by helping to define who *should* be accessing table resources.

Composition is a powerful way to merge modern workplace practice with emerging technological trends to support collaborative knowledge work. Such systems have the potential to increase the effectiveness of our personal devices, and increase the impact of workers contributions. Availability of an embedded control surface augments mobile devices and provides a social integration point adding to the cohesiveness of the collaborative table. What do you bring to the table?

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