The WeSpace: The Design, Development, and Deployment of a Walk-Up and Share Multi-Surface Visual Collaboration System

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ABSTRACT

We present WeSpace – a collaborative work space that integrates a large data wall with a multi-user multi-touch table. WeSpace has been developed for a population of scientists who frequently meet in small groups for data exploration and visualization. It provides a low overhead walk-up and share environment for users with their own personal applications and laptops. We present our year-long effort from initial ethnographic studies, to iterations of design, development and user testing, to the current experiences of these scientists carrying out their collaborative research in the WeSpace. We shed light on the utility, the value of the multi-touch table, the manifestation, usage patterns and the changes in their workflow that WeSpace has brought about.

Author Keywords

horizontal display, shared-display groupware, multi-monitor interfaces, collocated collaboration

ACM Classification Keywords

H.5.3. [Information Interfaces and Presentation (e.g., HCI)]: Group and Organization Interfaces.

INTRODUCTION AND MOTIVATION

The quantity of data that is pouring in from data and image capturing instruments, sensor networks, computer networks, and the web is ever-growing. The need to share, to search and explore, to manipulate and to make sense of these massive data collections has brought forth new human-computer interaction and display design challenges.

In recent years, multi-megapixel data walls and multi-user, multi-touch sensitive tabletop displays have become commercially available, offering tantalizing potential. These new form factors can offer larger physical areas and more pixels for information display and interaction. Questions remain as to whether and how these devices can actually benefit data-intensive, collaborative visual computing applications. In order for these emerging large display data walls and multi-touch digital tabletops to move out of their infancy to become a staple for the day-to-day collaborative visual computing and interaction, tangible benefits need to be shown. In light of this need, we have set out to address two research questions: (a) what are the key computational functionalities that will either enable the day-to-day usage of a multi-surface meeting room? and (b) can such a visual collaboration workspace change users' workflow processes for the better? In this paper, we present evidence that computational collaboration tools, appropriately built with new emerging display form factors, can indeed improve the day-to-day group work practices and collaboration in new ways, and can, most importantly, change scientists' workflow processes for the better, enabling new discoveries.

We present our research of a multi-surface collaboration space called *WeSpace*, a general-use tool for workplaces in which simultaneous visual exploration rendered from multiple data sources by multiple people is a crucial part of the work-flow process. WeSpace is the outcome of close collaboration between our research team and a population of scientists – astrophysicists from the Harvard Smithsonian Center for Astrophysics (the *CfA*). It is designed to enable modern day-to-day spontaneous collaborative sessions that are mediated and augmented with computational display devices. We report our year-long effort, starting with a period of ethnographic studies, utilizing a combination of Contextual Field Research (CFR) and intensive interviews, to iterations of design and development, and final results of actual user evaluation.

Figure 1. Astrophysicists meeting in the WeSpace.

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RELATED WORK

Many research projects have studied digital meeting room systems and interaction techniques in supporting multi-surface environments. The work reported in this paper is the first effort we are aware of that has put a multi-surface environment into actual use by a scientific user group.

Collaborative Infrastructures

Previous work in this area has focused mostly on providing low level infrastructure for cursor and screen sharing, moving data among display devices, and representation of visual layout of the room displays and objects within.

The *Collab* system allowed teams to work together or remotely on multiple desktops and a large display wall [24]. Dynamo allowed users' media to be moved to a shared display [13].

Streitz et al. have described digital furniture and interaction techniques designed to support spontaneous collaboration [25, 20]. Their designs included tabletop (*InteracTable*), vertical displays (*Dyna Wall*), and chairs (*CommChairs*) with built-in displays. They provided mechanisms for users to dynamically interconnect laptops and various furniture components to construct ad hoc collaborative spaces. Rekimoto and Saitoh [21] described a technique for users to move graphical objects from their laptop computers onto table and wall surfaces and among laptops in a workspace. Similarly, Shen et al's *UbiTable* was also intended to provide a mechanism for spontaneous, walk-up-and-use functionality of easy sharing of data, such as photos and notes [23]. In a subsequent effort, Everitt et al. provided mechanisms for interaction and document transfer among vertical displays, a table, and portable devices [7].

The *iRoom* project aimed to investigate and build seamless interactive spaces [16]. To enable this, the group built the *Point Right* system, which enables a mouse and keyboard to control any device connected to the system [17]. It enables a user's complete control over the environment while remaining seated at a meeting table. Several projects have been based on the iRoom infrastructure. These include the *Multibrowser* project, which allowed web content to be moved across multiple displays 18, and a system to support meetings of architects for building design [8].

Several efforts have addressed the mismatch between the continuous 2D motor space and the 3D display space that arises when navigating a pointer among various, non-aligned displays. Biehl et al. described the *ARIS* system that uses a flattened display environment, representing every display in the virtual space. Manipulations to the iconic representations in this display, such as moving on and between screens, are conveyed to the object [3,4]. Baudisch et al. introduce *Mouse Ether* [2], which attempts to unify multiple coplanar displays into a larger motor space, and Nacenta et al. presented the *Perspective Cursor*, which attempts to map the 2D motor space of the mouse to the image plane of a single viewer [19]. Wigdor used the *world in miniature* metaphor, present on the table miniature views of the vertical display [30]. Forlines et al. presented a system which uses vertical displays to present views from cameras, the position and orientation of which are controlled from the table [10].

Techniques also exist for simultaneously viewing data from multiple sources. Multiple applications can simply be run side-by-side on the same computer, or screens from many machines can be compared using screen sharing software, such as VNC (www.vnc.com). Wallace [29] and Tan [27] described systems for putting application windows or parts of a window from separate user desktops or laptop systems on a single display.

Productivity and Collaborative Processes

A key contribution of this paper is the field-work which shaped and then evaluated the WeSpace. A number of previous works have examined the efficacy of various visualisation and display technologies in controlled settings. With respect to work practice differences imposed by different display types, Rogers and Lindley [22] offer a set of observational user studies comparing vertical and horizontal interactive displays in a city tour planning task. Tan et al in [26] showed that large displays can improve productivity in spatial tasks, while Ball and North 1 showed potential performance benefits of large displays in low level navigation and visualization tasks.

IMPROMPTU is a framework presented recently by Biehl et al. that provided facilities to share each user's off-the-shelf applications in multiple display environments [5] and has been field used by co-located software developers. The IMPROMPTU system is similar to the system we will present, with key differences. First, IMPROMPTU positions shared user-interface elements on private display, while WeSpace utilizes a shared display. Second, the WeSpace provides live images of users' entire desktop on the shared display, IMPROMPTU shares applications at the *window* level. Finally, IMPROMPTU utilizes each laptop's pointer for input, while the WeSpace utilizes a shared multi-touch table. We will examine the needs which led to these differences in the WeSpace later in this paper.

In addition, one large shared touch display whiteboard system that has been studied in situ is the MERBoards [12, 28]. Tollinger and Huang studied how NASA engineers used multiple MERBoards that were integrated into an environment of workstations, desktop displays and large projection displays within the context of the actual NASA JPL Mars Exploration Rover (MER) mission. One of the interesting findings in 12 is that the MERBoard was valuable in supporting tasks that were new and have not been "proceduralized" yet. In some sense, the work presented in this paper addresses one the problems reported in 12 that some scientists preferred using PC projectors to the MERBoard because of the relative ease of plugging a laptop into a projector when compared to loading one's files onto the MERBoard.

ETHNOGRAPHIC STUDIES

Our goal was to develop a general tool to support scientists conducting collaborative research across disciplines. As a first step, we began by seeking out a research group to serve as partners in a participatory design process.

We chose the Coordinated Molecular Probe Line Extinction Thermal Emission Survey of Star Forming Regions (*COMPLETE*) group (www.cfa.harvard.edu/COMPLETE). The group is composed of professors, researchers, and graduate students. The group was selected largely because initial discussions indicated that they have challenging needs for a collaboration tool. We believed that satisfying such a group would yield the strongest possible outcome.

Research Instruments

To ensure that whatever system we developed provided an easy transition between the meeting and the remainder of the work process, we conducted intensive interviews with 4 members of COMPLETE located at Harvard, as well as an additional 6 astrophysicists at Harvard not in COMPLETE. The goal was to gain a high-level understanding of their work flow. Simultaneously, we also observed group meetings in order to begin to build our interaction models, and to understand the portion of their process our tool would be built to support. We now review the results.

Users and Tools

All participants interviewed described a need for better tools to support their work. As the process continued, it became clear that the development of useful software would be significantly hindered by the highly variable individual practices of each member of the group. Of the many variables, two in particular would be highly inhibitive:

Disparate data types: research teams in any discipline commonly examine different elements of a problem. Data sources and types examined by the COMPLETE team vary widely within a project. For example, the group utilizes a various telescopes to measure in all of radio, near and infrared, sub millimetre, and optical bandwidths. Astronomy data is commonly saved as a single file type, but the content of these files is highly variable. Often, only the person creating the file will be able to interpret its content.

Different and Custom Software Tools: due in part to the high variability of data types, tools employed by members of the group also varied. Viewing applications are highly specialized, and mostly created by research teams and not software developers. Collaboration is further complicated by the high-level of customization and augmentation of these tools. Many group members write their own software in various languages (eg: C, Perl, Python, IDL), the output of which often does not conform to any standard.

It was clear that our tool would need to support any number of data types, as well as custom software utilized by the various participants. As such, any tool that requires the users to execute applications on a server would not be suitable. We expected this particular outcome to drive much of our development process.

Current Practice: Workflow

COMPLETE is dedicated to conducting and analysing the results of a survey of regions of space. The researchers are concerned with producing two types of research products. The first is raw data, which is publically released following an embargo period. The second is research papers that describe the regions of interest and provide analysis as a novel scientific contribution. Because it constitutes a much larger portion of their time, we will focus on the publication process. To conduct part of the second phase of their project, the researchers described to us a 4-stage process:

Proposal Preparation: in order to conduct a higher-resolution observation of a particular region of space, a team must submit a formal proposal to the agencies operating the various telescopes. In the proposal preparation phase, members of COMPLETE perform analyses of their own previously collected data, of raw data from other sources, and of published works. From these, they must provide a proposal outlining the benefits to science of allowing the new high-resolution observations to take place.

Data Reduction: if their proposal is accepted, the observations are conducted using the particular telescope as instructed by the researchers. The newly acquired raw data usually requires significant massaging before analysis can begin, including file format conversions, applying transformations to account for known instrument peculiarities, filtering to remove noise and unwanted features, and almost always transformations to adjust the content of the data to suit the analysis.

Data Analysis: analysis is typically performed within the context of the proposal, confirming or refuting hypotheses. This stage of the workflow can introduce an interesting problem: often, researchers wish to be highly collaborative with one another. Due to the previously discussed problems with data types and custom tools, the amount of collaboration is often limited to e-mail exchanges, often with data reduced to raster image files to ensure compatibility between collaborators.

Write-up: after analysis, the researchers will typically write-up their results for publication. As with any research area, writing too is usually a collaborative process among the authors of the paper.

Current Practice: Group Meetings

We attended several of the COMPETE group's regularly scheduled meetings over a 2-month period: observing, photographing, and taking notes on their current practice. The group treats the meetings as an opportunity to synchronize activities among the members through status reports, to receive guidance from other members, and to discuss current research.

As each member of the group is given the floor, the meeting room's projector is connected to and driven by that member's laptop. The content shown on the projector varies widely based on the circumstances of the meeting, but typically falls in to one of two categories.

Documents, such as a research paper or proposal in progress, or a previously published work, are typically shown on the display to solicit feedback or to provide evidence to support a position during a discussion.

Data, such as observations from telescopes, are usually shown after one or more members of the group has spent a significant amount of time analysing it.

It occurs frequently that one or more members of the group wishes to share data or documents simultaneously to support the ongoing discussion. To facilitate this, they will typically position one of the laptops in such a way to allow others to see (the *laptop-sharing* strategy), or will attempt to pass their data to the laptop connected to the projector (the *data passing* strategy). In the case of the laptop-sharing strategy, the size of the display inhibits other group members' examination of the data. The data-passing strategy is inhibited by the disparate data types and custom tools we described earlier: often, the members will take a screen shot or output a raster file to ensure the proper visualisation is shown when passed to the other user's machine. This strategy removes the ability to further manipulate the data and imposes significant overhead.

Opportunities for Collaboration

While the regular group meetings demonstrate a need for a low-overhead meeting tool, interviews with group members suggested another opportunity to enhance the scientific process. As outlined earlier, the workflow for each research product is typically composed of 4-steps: *proposal preparation*, *data reduction*, *data analysis*, and *write-up*. Each of these steps might require contributions from more than one member of the group. The practice of the group at the time of our study was typically to engage in asynchronous and spontaneous collaboration. A researcher engaged in *data analysis*, for example, might encounter a formation or image that requires further analysis from another researcher with different expertise. At that point, the first researcher might e-mail a screenshot or textual description of the image (resulting in a low-fidelity artefact), or might schedule a meeting to discuss the finding (resulting in a slow-down in the process).

As we continued to interview the group members, it became apparent that there was a desire for synchronous co-located collaboration at various phases of their process. Nearly all of the group members indicated that they would prefer to conduct spontaneous face to face meetings to do their work together. Each expressed frustration that their current tools and facilities did not properly support such collaboration, and were, at times, a burden rather than an aid to their workflow. In interviews, we discussed what a new tool to support collaboration might need in order to properly support their processes. These discussions yielded a list of requirements for such a tool, some of which were suggested by the users explicitly, while others were determined from analysis of their input.

System Requirements

Provide a sharable display: the current primary opportunity for collaborative science is during group meetings. At these meetings, the lack of a large, shared, high-resolution display limits the data that can be shared and imposes an overhead on to their work practice. The ideal environment would include displays that would sufficiently allow the researchers to share their work with the group, while also functioning at a high resolution. Multiple data visualizations need to be rendered simultaneously to facilitate easy comparison, overlays and collaboration.

Allow the use of their laptops: because of the necessities of using different data types and custom software, the collaboration tool must allow the scientific users to run applications from their own native laptops while visualizing and analyzing the output rendering on a shared display.

Maintain interactivity of existing applications: as described above, the current collaborative practice often requires sharing screenshots of applications with one another. The ideal tool would allow data being shown on the large display interactively, within the application generating its view. This allows for a faster iterative process, while maintaining the fidelity of data.

Retain user control over their own data: when presented with the idea of a tool to replace the practice of sharing screenshots, all members of the group were initially enthused. However, many engage in collaborations with researchers who are not members of COMPLETE. On such occasions, each of the collaborators needs to maintain control over their own data, ensuring that only those renderings and projections they choose are shown, and that proprietary underlying data are not shared.

Support egalitarian input: frequently, a discussion will involve input and data from a diverse group, each of whom bring a different expertise to the table. Interviews with users indicated that a system that supports such collaboration must allow group members to have equal opportunity for control of the discussion at all times, preventing a single user from exclusively controlling the system and thus the conversation.

Provide a record / work product at the meeting: the working meetings we observed often involve a great deal of collaborative work product: diagrams, discussions of research direction, and text for publication. This product is often drawn on a whiteboard, hastily jotted down, or never actually recorded. Several group members insisted that the tool we built should have functionality to collaboratively generate and to store work products. It is important to distinguish work product from meeting logs: the group members desired a tool to produce tangible, useful piece of text, data, or imagery, and not a facility to search logs looking for elements which might have been used to produce these.

DESIGN CONSIDERATIONS AND IMPLEMENTATION

Our ultimate goal in the development of the WeSpace is to create a collaborative visual computing space for users to walk-up and share with minimum interruption to their day-to-day scientific practices. Details of the system implementation of the WeSpace, as well as a video of its use, can be found in [15]. In this section, we discuss some elements of its implementation.

While we viewed it as important that the WeSpace meet each of the user-driven system requirements designed previously, we also took it as a central tenet that it was essential to provide an extensible system for the analysis of visual data. Images of user applications, therefore, must pass-through the processing pipeline of the WeSpace, to provide an opportunity for the development of image-processing.

Existing models of sharing user laptop contents fall short in many respects in fulfilling our user requirements: 1) Provide VGA/DVI cable(s) to connect to a single projector or multiple projectors, the most common and simple solution today, does not provide a facility to produce collaborative work product, or to easily overlay and compare the data from more than one user's laptop. 2) Upload data to a shared compute server with native viewer applications [14, 13, 20, 30]. This ensures good rendering performance. However, viewers and tools used by scientists are often customized and can include software they wrote themselves, making configuring such a server prohibitive. This solution would also require that users relinquish underlying data. 3) IMPROMPTU: the system described by Biehl et al. provides for the sharing of application windows across multiple systems and displays. While this system provides for many of the requirements we have described, it does not meet them all. First is their decision to provide user interface elements on the private display of each participant. While useful for the group they are seeking to support, in a visual collaboration space, such as the WeSpace, the large shared displays are the focus of collaboration. The distribution of user interface elements across the smaller displays detracts from this focus. Second, the IMPROMPTU system provides no mechanism for the processing of the live images of the desktop applications, making image processing and overlay impossible without extensive modification. Last, the IMPROMPTU system uses users' mice as the input mechanism to the system. To support a collaboration space, we have found that a shared direct-touch interface helps users maintain a focus on the visual data, and better supports egalitarian input.

Indeed, an earlier version of the WeSpace did not use a touch-table, but rather relied on mice and other pointing devices for input. In this early version, each laptop's mouse pointer could move among all of the windows shown on the wall-display – including other users' laptops. Based on early design iterations with our target group, the touch-table was added to the system to make input more egalitarian, to make input visible to other users, and to remove confusion over mouse-pointer mapping when multiple mice were present in the system. Subsequent design iterations lead to the modification of the table interface to further promote egalitarian input and awareness.

Here, we will describe those elements of the system which were critical to its success, and which underwent changes as part of the iterative design process. For more details about the design itself, we refer the reader to [15].

Display Ecology & Infrastructure

The WeSpace includes a large high resolution display wall and a multi-touch tabletop, both driven by a WeSpace server machine. Laptops or desktops can be brought into the space on-the-fly. The multi-touch tabletop is 4 feet by 3.5 feet including a 7-inch non-touch sensitive border around the tabletop, providing comfortable seating for three or four participants (see Figure 1). The table is situated in front of the display wall, to provide a means for egalitarian input and to facilitate fact-to-face collaboration. Control events are passed amongst the laptops, the data wall, and the multi-touch table, allowing all participants to control from each of the laptops or the multi-touch table. Through the table, all elements of the system can be controlled: native applications, as well as individual laptop displays.

The current implementation of the WeSpace server is built in Java running on a 3.2GHz Windows PC. The server drives a 10ft by 5ft rear-projection Megaview data wall with a resolution 3072 x 1536, and a DiamondTouch tabletop [6] with a projected resolution of 1280 x 1024. We use OpenGL (jogl) to render live screen images and user interfaces. With four clients connected and displayed, both the wall and the table update at the frame rate around 15fps. The software infrastructure is based on screen-sharing techniques, sending live computer screens to the server over the network. This allows a user to launch any application on their own laptop and share its visualization, and the server software to have flexible control over those visualizations as a rendered stream. User customization and data protection are simultaneously supported.

A lightweight client is installed on each laptop. Group members may use either Ethernet cables, or WiFi to connect to the server. We provide clients running on both Windows (XP & Vista) and Mac OS X. We leverage tools which utilize the VNC protocol to share displays.

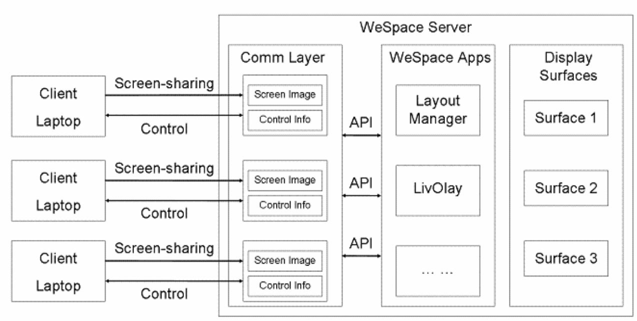

Figure 2 WeSpace software architecture.

WeSpace Native Tools

The WeSpace APIs allow development of user defined applications. As of now, two such applications have been developed in our environment: the Layout Manager, and LivOlay. Users may launch into one of these applications by tapping on the corresponding icons that are portals to these applications on the multi-touch table.

Layout Manager enables users to control the layout of connected laptop screen images on the shared surfaces. Both synchronized and asymchronous views are supporteded between the tabletop and data wall: what a user sees and manipulates on the tabletop has an identical visual correspondence on the wall.

Each client laptop connected to the space is assigned a display status: *important*, *public*, or *private*. An important laptop's display is enlarged and highlighted on the shared surfaces, while a screen with public status will appear relatively small. A private screen indicates its owner's desire for privacy, thus will not be displayed on the shared surfaces. Figure 1 (left) shows a WeSpace session where one user laptop is important while the other two are public.

Status controls are provided on each laptop's native client interface, as well as rendered next to each laptop's screen on the table. When a display's status changes, an automatic layout change is applied and the transition is animated to ensure visual fluidity. Users can also use gestural input on the tabletop to control size and position of laptop images.

In layout Manager, the multi-touch tabletop also performs input on the connected laptops. Double-tapping a laptop's image on the table severs the synchronized view between surfaces: the wall keeps the layout display of multiple screen images, while the table zooms in to a full-screen display of the selected laptop. User actions on the tabletop are interpreted as mouse input and sent to the client laptop.

The use of the tabletop to control the Layout Manager evolved in the later stages of our iterative design process. This occurred primarily out of the reported confusion users experienced in tracking their mouse pointer across multiple displays, and in keeping track of other users' actions. We found that the tabletop's direct-touch input eliminated the need for pointer tracking, as well as making visually apparent what other users were doing with the system.

LivOlay,was developed as part of an early iteration of the WeSpace. It is implemented using the WeSpace APIs, and is intended to facilitate easy visual exploration and comparison of imagery from multiple laptops. Although he Layout Manager allows the enlarging of two laptop displays to show them side-by-side, during our evaluations it became apparent that there was a need for users to *overlay* live imagery of applications running on the laptops. LivOlay works by users selecting corresponding landmark points in visualizations to be registered for overlay. An early version without the mult-touch table support of LivOlay is presented in [14].

In the current implementation, the multi-touch tabletop acts as the group input and command centre for visual exploration tasks. When the team first enters LivOlay, they select application windows to overlay by tapping them on the tabletop. The application boundaries are acquired using the WeSpace API and are visually highlighted.

In LivOlay, the large-size, high-resolution data wall provides two view modes to users: a linked view and an overlapped view (*left* and *center* of Figure 3). In the linked view, applications are displayed side-by-side, each showing registered points as well as links to corresponding points on other application images; in the overlapped view, live renderings are overlapped according to the transformation calculated using their registration points. Users can switch between the two modes by tapping a button on the tabletop.

LivOlay we emphasizes the role of the interactive table as the command center in the multi-display environment. Identical toolbars, are designed and displayed along each edge of the table to ensure egalitarian input (Figure 3 *right*). To register a point in one application, pick a pin on the toolbar, and drop it on the target position. The transparency of the current application in the overlapped visualization is controlled by tapping or sliding the slider in the toolbars. Also, a "Table Mode Switch" button appears in each toolbar allowing users to switch to or out of the overlapped view of those applications on the table. When the table is in the overlapped view, it's synchronized with the wall display: visual explorations, such as zoom, pan and transparency change are reflected on both surfaces. With a stylus, users are able to annotate directly on the overlapped visualization displayed on the table.

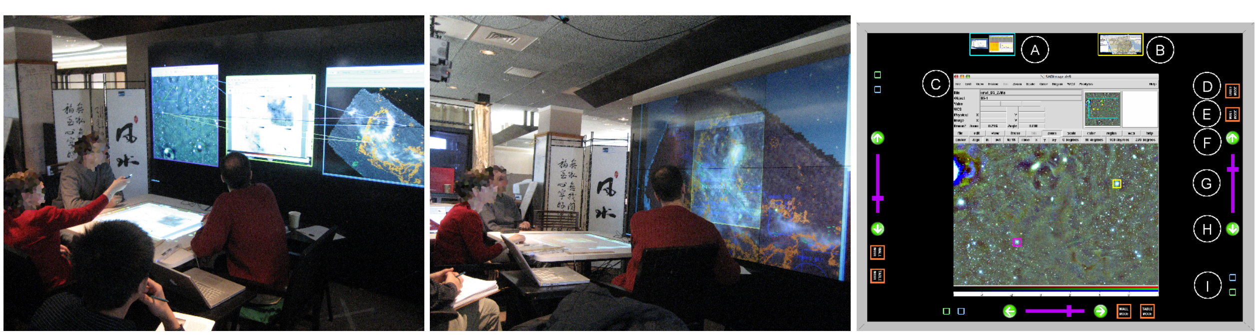

Figure 3. LivOlay in use. (*left*) Linked view of 3 registered images. (*center*) Overlapped view of the same 3 images. (*right*) A screen shot of the multi-touch tabletop ((A) Portal icon to Layout Manager, (B) Portal icon to LivOlay, (C) an astronomical data viewer (DS9) image to be overlaid, with registered points displayed, (D) wall mode switch, (E) table mode switch, (F,H) load next/previous application, (G) transparency control slider, (I) unused registration pins, pick up and drag to target position to register a point.)

EVALUATION

After the final design iteration with our target group, we again made WeSpace available to them. Three researchers (*MB*, a research assistant, and *JK*, and *JF*, graduate students) conducted collaborative research sessions in the WeSpace. Face-to-face collaborative research sessions are not normally part of their workflow – it is rather the type of sessions the users indicated that they would like to add to their workflow, and which WeSpace is intended to support.

We wished to determine the value of the space and the addition of collaboration to the workflow in general. MB and JK had been present at every iterative design session, and JF had been present for most of them. These sessions varied from our regular design iteration meetings in that we asked the participants to immerse themselves in their research experience, and not to spend any time explaining concepts or engaging us in design discussion. The group members brought their actual, current research materials with them on their own laptops, with the intention of discussing their current work and actually performing their scientific process during our observation sessions.

We observed the meetings and took notes of interesting events, video-taped the sessions, and logged input and system events. To understand the impact on their workflow, we asked members of the group to describe their experiences with the system, and to explain how their workflow was affected by its use.

The results were quite positive. Conducting these collaboration sessions was extremely beneficial to the users, and actually resulted in new research products. In the following sections, we will examine the data collected from this final session and post task feedback. In some cases, this feedback addresses not only the final prototype, but also the positive disruptions the users foresee to their research process – also a contribution of this work.

Post Task Feedback

In this section, we report verbatim from post-task feedback written by our participants. Our intention is to validate our process and our designs and, just as importantly, to point others in similar directions when building systems for collaborative research.

According to user feedback, the addition of collaboration in the WeSpace to the actual scientific workflow was extremely valuable:

From my perspective of studying outflows[1] and shells[2], what our two WeSpace sessions allowed me to do is look for evidence of outflows and shells in data sets that I may not normally look at, and look at these data sets with experts that work with them on a daily basis. It is true that, if I had thought "what does my outflows look like in other wavelengths?", I could have tried tracking-down all the data myself, tried to look at them side-by-side or do some form of hack overlay, and then if I was confused track-down one of the experts (e.g. JF or JK). But this scenario would be quite unlikely to happen due to a technological and social-effort barrier. However, being put under the circumstances of the WeSpace, it was all easy (like, really really easy!).

Functionality Benefits

Our own observations indicated that the software was robust and facilitated the users' research. In this snippet from the post task feedback, one of the users describes how the particular functionality of the WeSpace helped in performing data analysis:

Another note on my own research, I have already detected the outflows and shells for Perseus using other methods and am prepping the papers for publication. However, what the collaborative meetings with WeSpace (and specifically using LivOlay) allowed me to do is confirm whether the newly discovered features I found in the radio wavelengths are observable at other wavelengths. Outflows and shells are very good candidates for these kinds of multi-wavelength studies because you can see in different forms. (In the radio, I see the actual gas emission. In the optical, I see the shock fronts where outflows & shells are impacting the visible dust). I will probably include some of JF's images in my papers (or similar images) with my outflows/shells overlaid to prove "here are my new features at other wavelengths thus they are real".

Process Changes

We intended the WeSpace to serve not only as a support tool, but also as an enabler for the introduction of collocated collaboration in the early stages of the COMPLETE group's scientific process. Here, one of the users describes how their process was affected.

Use of the WeSpace definitely is different than our normal work procedure. It basically takes some of the "usual" workflow steps and makes them much more efficient and convenient, and introduces new "steps" that are extremely helpful.

Here, the same user describes first the usual procedure for processing new observations, and then how the WeSpace changed this process for the discussions held during the session.

Traditional Process: *I (or a generic astronomer) gets some new data. After I have reduced and cleaned-up the raw data, I inspect it: what sources do I see? What known and new features are there? Are there artefacts or noise that shouldn't be there? Once I identify the "points of interest", I go into my data and start to analyze, measure, and identify stuff. And, if I'm a good astronomer, I then compare my data (be it the actual image or at least the location of interesting features) to other published papers, and data (either published or from other collaborators). This may turn into a cyclical process where I will identify/research the feature, go take more measurements or refine my image, then go back and identify/research some more. Eventually, I'll settle on what is new (be it a feature or calculation/measurement) and publish it. Then write an observing proposal to conduct follow-up observations, get data, and start the whole process over again.*

[1] Outflow, more accurately bipolar outflow, is the physical phenomena associated with the stage of star formation where gas that is collapsing onto a forming protostar is ejected due to angular momentum as collimated flows along the star's poles.

[2] Shell: a relatively generic term for the phenomena where gas and dust is spherically blown away from a source. Examples of shells include super nova (the source of the shell is an exploding star), or "spherical winds" (a shell produced when a star emits enough radiation to cause a wind).

Process Changes with WeSpace: *where WeSpace changes things is in this middle iterative process of exploring your data. So, JF came to our session at the stage of "I have brand new data from my telescope and have no idea what is in the image". LivOlay allowed him to easily and rapidly explore his data and compare it to other data sets and catalogues of known features (both in published and unpublished images). Better yet, the WeSpace set-up allowed JF to conduct this exploration with not only the data sets he thought were important, but the data sets JK and I thought were important thus broadening his analysis. JK and I came into the session with data sets we had already picked-apart and explored, but with the tantalizing sneak-peak of JF's images at the regular group meeting [we] decided we wanted to see if his data could shed any light or new inferences on our data.*

These changes to the workflow are described by the user as being positive and useful. As for ease of integration in to their work practice, user MB noted in particular that:

Now that I know it is so easy, I will be far more likely to put the use of WeSpace into my workflow.

Moving forward from the collaborative session, each of the group members will continue to work on the results found during their meeting. A user describes the

WeSpace definitely enhanced and improved our working experience. At this point all three of us are back to re-investigating our data independently. Either each will decide that there is nothing new to learn with the current data sets or that there are some new possible features of interest (based on the post-session independent work), and getting back together would be useful/merited. If this system were conveniently at the CfA, I could see it easily being incorporated into an astronomer's workflow (in addition to other collaboration meetings/presentations). And LivOlay on its own would be a wonderful tool for astronomers to use on their own computers. Also, having publication quality/resolution versions of the LivOlay images would be fantastic.

Value of Collaboration

In addition to the value of the WeSpace as a tool, our studies were also intended to determine the value in general of the addition of collocated collaboration to a scientific team's workflow. To this point, one of our users noted:

I went into the WeSpace session anticipating we would make great new discoveries and gain a better understanding of our data (which we did). However, what I did not expect was the amazing value in the collaborative working. Sure, I thought that the WeSpace would be good for things like COMPLETE meetings where it is hard to show each other what we are working on and compare. What our sessions showed me was that working with others is a wonderful resource and of great value. Normally I only get others' opinions when I'm at the stage of "here are my results, let me show you" or "my code to reduce my data is broken, can you help me fix it?" However, working side-by-side with people of different backgrounds who are interested in the same data was fantastic!!! It was extremely productive, useful, and insightful.

The same user goes in to great detail about how the face to face meeting allowed the users to work collaboratively to quickly identify interesting features, made evident by overlaying data sets that JF and JK would otherwise have been working on separately: *[WeSpace] definitely helped in the analysis of papers that each of us is working on. In the case of JK and MB, we explored data (sic) that we had already compiled/analyzed but within the context of other data sets (and with other collaborators) than we normally would have used worked-with.*

Other than giving all of us a better understanding of our data, we did identify one particular feature that was striking in one of JF's images - what appeared to be a dense blob of gas with a cometary tail on it. Then putting it within a context of my and JK' data, we realized that there was a young source[3] inside of the blob driving an outflow, and that the outflow lobes are bent in the same direction as the cometary. So the question is what is the cause of this feature? We realized based on data overlays that two possible sources for wind could be a young cluster of stars in the direction of the tail, and that one of my newly identified shells in the region could be expanding into it.

As the user described, because of collocated collaboration, and the presence of experts bringing more than one data source to the discussion, new discoveries were made. The user notes:

Thus, we worked along with JK to write an observing proposal!

Each of the users credits their face to face meeting and the tools in the WeSpace with enabling this discovery. They note that it might not have occurred without the face to face collaboration enabled by our tool.

In addition to this proposal, there were additional scientific outcomes from the two sessions we observed.

Tangible Outcomes

The clearest evidence of the success of the WeSpace and the addition of collaboration to the COMPLETE group's workflow are the multiple, tangible scientific outcomes produced during the sessions. In all, the users reported that the work done during the sessions will enable them to submit a new observing proposal, as we describe above, as well as three scientific ongoing journal papers, as well as another not yet named:

JF will eventually write a paper officially publishing the optical images we were looking at with him. (sic) Also, the three papers listed above plan to be submitted for publication within the next couple months.

As we have described, the users found significant value not only in the WeSpace as a tool, but also in the positive process changes it introduced to their workflow. In particular, the group members found great value in the collaboration it enabled, and in the new discoveries that this collaboration allowed them to make during our session. The value of the workflow changes, collaboration, and discoveries is clearly demonstrated by the tangible outcomes from the session: significant content from 4 papers, and a new observing proposal which otherwise would not have been made.

[3] Young source: is the term used in astronomy, specifically star formation, to refer to a young star still forming or newly formed.

Observations & Data Logging

General Observations: It is apparent that JK, MB and JF know each other very well and have been working together for a long time. The collaborative discussions were engaged and focussed. Much time was spent on visual inspection of data on the wall and on the table. We were happily surprised with the fluency in which they moved data in and out of their own laptops and onto the group space on these surfaces. Over the long hours of the meeting sessions, we observed: continued verbal utterances by all group members in turns; all three felt comfortable touching and inputting from the multi-touch tabletop; they all contributed data and documents frequently from their respective laptops; laser pointing to the pixel location of interest on the wall by one participant while touch gesturing to zoom in and out the visual data by another person often was seen.

The Value of the Multi-Touch Table: The multi-touch table in the WeSpace has proven to be conducive to these collaborative visual explorations. In particular, the tabletop has been observed to be very useful in supporting two aspects of this type of scientific collaborative work. First, it created egalitarian input and navigation amongst the group. Our users felt at ease in reaching out and touch-operating their visual data. The recorded data analysis discussed below confirms this. A second utility of the tabletop is that its horizontality afforded the group to use physically tangible tools on top of the digital data. For example, they used a wooden ruler to measure the distance between stars on the digital display of the tabletop. They also frequently used a stylus we provided to mark and annotate their work product, a fluid integration of physical to digital worlds.

Recorded Data: During the evaluation sessions, our system recorded the number and type of input from each of the scientists participating in the session. Using these logs, we were able to begin to address questions concerning the relative contribution from each group member in terms of controlling the system, and directing the conversation.

Overall, the relative contribution from the three group members in the number of input actions was fairly equal, with a distribution of input of 22%, 33%, and 45% for JK, MB, and JF respectively. This stands in contrast to a group's use of a single-user system: member controlling the mouse and keyboard greatly influences the conversation.

While the distribution of input was fairly equal when the meeting was viewed as a whole, a different story emerged when we examined input from each of the three users over time. Figure 4 shows the relative number of input events performed by each of the three users for each 5 minute time period. While the overall distribution of input was relatively even, the distribution during the 5 minute samples was not. The logs suggest that the control of the system passed from user to user at different times during the meeting as the participants took turns directing the conversation. While the majority of input was normally made by one participant, it was rare to see any one user monopolising the table. These patterns match our observations of the meeting that the scientists took turns introducing new data and hypotheses, with their colleagues reacting to these additions.

Lessons Learned

In conducting our iterative design process, we learned several lessons that will inform our future approach.

Make the Process Win-Win: as with any iterative design process, our results demonstrate the importance of participants perceiving benefit. What we found to be equally important, however, was conducting our in-lab iterative design sessions around actual meetings, where our target users were simultaneously undergoing their scientific process. We found that ensuring that each individual meeting, and not just the end product, was helpful to their process ensured more productive iterations.

Set expectations: our goal was to produce a useful system for our target users. We often found it necessary to balance the needs of our particular users with what would ultimately be beneficial to a wider audience. Also, our users were generally unaware of the development process, meaning they were often unable to understand why some requests could not be met. Setting expectations at the beginning and on an ongoing process was critical to our collaboration.

Let Participants Take Ownership of the Process: that users possessed a sense of ownership of the process was essential. We regularly met and solicited their advice not just in understanding problems, but also in solutions. Although these recommendations would not always be grounded, giving the users a sense of ownership did help in gaining their trust and in ultimately delivering the best design.

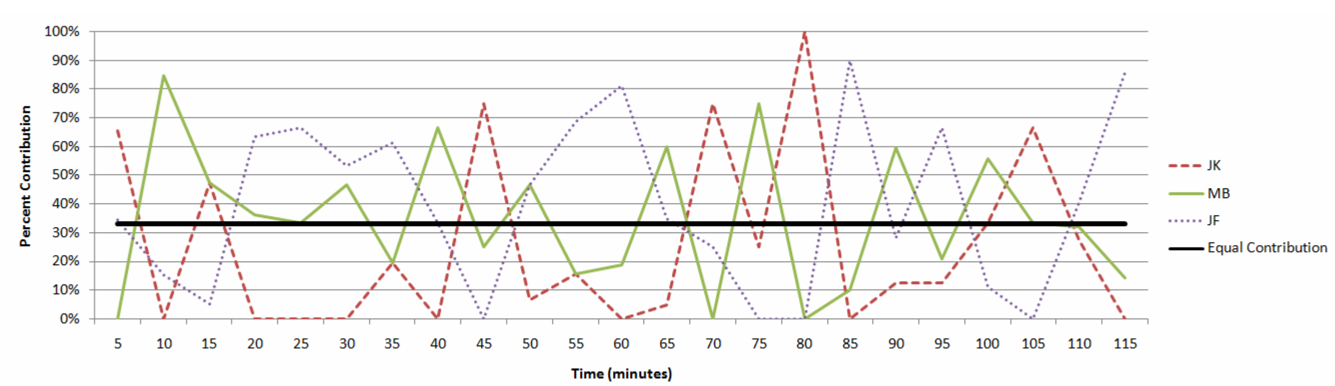

Figure 4. The relative input contribution from each of the three scientists over time. Overall, our three scientists contributed equally; however, each group member lead the control of the system at different points in the meeting.

CONCLUSION AND FUTURE WORK

WeSpace provides a low overhead user interface to seamlessly integrate and coordinate the interaction among large interactive tables, data walls, and personal computers and laptops. WeSpace also provides a set of native services and applications to facilitate collaborative exploration. The current set of services include functionalities to (a) layout and manipulate multiple live desktops on multi-touch tabletops and display walls, (b) select and pull-out any user-chosen applications from their own laptops onto the wall and the table, (c) enable visualization, overlay and mark up of live visual renderings from any of users' own applications, and (d) give all group members equal access to touch manipulation around a multi-touch tabletop. These functionalities enable collaboration participants to use the often highly customized visualisation software running on their own laptops, and avoid the hindering overhead of requiring users to copy data to a separate display system [12]. Users benefit from spontaneous walk-up collaboration, larger display areas, and multi-touch input models.

Designers seeking to apply our results should consider two elements: the design requirements we outlined, and the WeSpace system we implemented to satisfy those requirements. An interesting issue not yet fully explored is to examine the impact of the WeSpace in isolation, comparing its use with a modified practice in which users utilize some other method for face-to-face collaboration.

The next step in this line of research will be the evaluation of WeSpace with other groups of astrophysicists, not involved in the iterative design process. Once this is complete, we will begin the modification and deployment of WeSpace for use by other groups. The WeSpace system is designed to allow custom applications to plug-in to suit the needs of particular domains. We look forward to generalizing this workspace for a diverse set of group activities as we move forward.

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