The Impact of Display-rich Environments for Enhancing Task Parallelism and Group Awareness in Advanced Collaboration Environments

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ABSTRACT

The Continuum is a display-rich project room that allows distributed researchers to work together in intensive collaborative campaigns. In this paper, we describe iterative design study of using Continuum's display technologies to support enhanced task parallelism and group awareness. The study involves placing small groups of users in two Continuum spaces connected over a high-speed network and asking them to perform a variety of information discovery and knowledge crystallization tasks, while varying the technology configurations. The goal of this study is to explore the design issues for enhancing cooperative work in display-rich environments.

Keywords

Amplified Collaboration Environments, Synchronous Distributed Collaborative Work, Shared Workspace, Small Group Behavior, Iterative Design.

1. INTRODUCTION

An Amplified Collaboration Environment (ACE) [7] is a distributed extension of a war room or dedicated project room in which a group of people co-locate for several days to months to solve a problem together. A war room may contain numerous whiteboards, flipcharts, and corkboards on which the group members post information throughout the course of the meeting. These meeting artifacts are kept persistent during the course of the campaign so that group members can refer back to them from time to time. Prior research in war rooms has shown that in some cases productivity can be enhanced far beyond the corporate average [11, 23]. Tightly coupled work is often considered as a feature of traditional co-located teamwork, but it is now possible to realize an affordable environment for supporting intensive work between distributed teams. The goal of an ACE is to provide a future-generation collaboratorium by augmenting the traditional concept of the war room with technologies that permit distributed teams to make use of its problem solving benefits.

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The Continuum is an Amplified Collaboration Environment specifically targeted for supporting collaborative scientific investigation [7]. The Continuum uses an Access Grid (AG) node to support group-to-group communication [19], a passive stereoscopic display for sharing immersive views of 3D content [8], a scalable LCD tiled display that provides shared views of text documents, web pages, spreadsheets, graphs and charts, and high-resolution scientific visualizations, a shared plasma touch screen that supports collaborative annotation, and wireless laptops, PDAs (Personal Digital Assistants), and tablet PCs for remote access to the numerous displays. The Continuum Project is currently developing the hardware and software technology while studying the human factors issues in supporting an ACE.

We are currently investigating how the Continuum's tiled displays can be used in enhancing task parallelism and group awareness between distributed researchers during intensive collaborative work. Tiled displays are often used to project a single, extremely large, high-resolution visualization [2, 4, 13, 17]. It is our belief however, that for collaboration, a better way to use a tiled display is as a large distributed "corkboard" which allows meeting participants to pin up informational artifacts for all to see.

From our prior experience in developing tele-immersive environments, we have found that there are benefits to be gained when participants do not see the same view during collaboration [12]. By being able to tailor their individual views, collaborators can work in parallel on a problem. We observed that, within this real-time tele-immersive scientific data analysis exercise, participants tended to work independently for the most part and then

Figure 1. One of two Continuum Amplified Collaboration Environments at the Electronic Visualization Laboratory at the University of Illinois at Chicago. Top left is a collaborative passive stereoscopic display for showing immersive 3D content; next to it is a 2x2 matrix collaborative tiled display; next to it are vertically stacked plasma screens that are used for Access Grid multi-site video conferencing; to the right of this is the plasma touch-screen that is used for shared white-boarding; interaction to these displays via wireless access.

synchronize from time to time to share and discuss findings. We also observed that avatars were useful for the most part in maintaining group awareness but participants needed more continuous feedback of the partner's action or intention, such as signaling or illustrating certain actions to the partner, when using tailored views.

Over the past year, we have developed and examined a set of iterative design studies to understand how to support real-time collaborative information visualization. The study involves placing collaborators in two separate sites and asking them to perform a variety of information discovery and knowledge crystallization tasks using the Continuum. In this design study, we want to understand how the technology configuration affects the collaboration pattern and group performance.

This paper first presents the hardware and software technologies which we have chosen to implement the Continuum, and the rationale behind their development. It then describes iterative design studies focusing on exploring design issues for the Continuum technologies to better support real-time distributed scientific collaborative work. Finally, it discusses some important findings, lessons learned from this study, and ideas for future exploration.

2. THE CONTINUUM

The Continuum is intended as the future-generation collaboratorium for scientific investigation over high-speed networks that are connected to high-performance computation and data resources. Current off-the-shelf collaboration tools such as Microsoft's NetMeeting cannot support the kind of interaction that occurs in real science campaigns. Scientists want more than just being able to videoconference and share spreadsheets with each other. They want to be able to collaboratively query, mine, view, and discuss visualizations of enormous data sets in real time. The data sets that scientists routinely work with are on the order of terabytes. The visualization systems that are capable of displaying data sets of this size require more than desktop PCs.

Figure 1 is a photograph of the displays that comprise the Continuum at Electronic Visualization Laboratory (EVL) at the University of Illinois at Chicago. Two Continuum spaces were built at EVL to facilitate experiments in remote scientific collaboration. Another one is also operational at the Technology Research Education and Commercialization Center (TRECC) in DuPage County, Illinois. The Continuum consists of a number of modular technologies: multi-site video audio conferencing; interactive stereoscopic computer graphics and high resolution tiled graphics displays for content sharing;

plasma touch screens for collaborative annotation; and wireless mobile interaction.

The Access Grid [19] is designed to support group-to-group collaboration or participation in large-scale distributed meetings, seminars and lectures. A typical Access Grid node is driven by four PCs (video playback and navigation, video capture, audio, and audio panel control). The Access Grid also has four pan-tilt cameras that are distributed throughout the meeting room. This configuration affords each site the ability to provide multiple simultaneous viewpoints into a meeting. These viewpoints are important because a single camera simply does not have sufficient resolution and field of view to depict all the meeting attendees.

The scalable LCD tiled displays provide shared content views of text documents, web pages, spreadsheets, graphs and charts and scientific visualizations. The end goal is to support users to be able to manipulate remotely located contents collaboratively as if everything is being done locally. With that focus, EVL has developed TeraVision technology to support content sharing on the tiled displays. TeraVision is a graphics streaming system, enabling anyone to distribute contents from laptops, workstations, or even cluster node to remote collaborators over high-speed network.

The collaborative annotation is supported by shared touch-screen whiteboards on which collaborators may jot down notes and sketch diagrams. We uses a plasma screen overlaid with the Matisse touch screen, by SmartTech [18]. Users can interact with the screen using a passive pen or one's finger as they would with traditional dry-erase whiteboards.

Software interface to allow a laptop or tablet PC to navigate across any of the displays on the Continuum is developed in order to encourage users to work on these displays collectively.

3. THE DESIGN STUDY

In this section, we briefly describe the progress of our iterative design of the Continuum technologies and the lessons learned from each study. We conducted a pilot study then four iterative design studies with the technology variations.

Nineteen computer science graduate students from EVL participated as volunteers in this study. All have experienced computers and collaboration technologies, such as e-mail and instant messaging, and some of them have used NetMeeting or other commercial/research online meeting room systems. They all expressed interest in using the Continuum technologies and working as a team.

3.1 The Pilot Study

A pilot study was conducted to evaluate the task and the initial system configuration design of the Continuum technologies. A group of three students solved a set of collaborative problems: first divided between two sites on the first day, and then again co-located in the same room on the second day.

The pilot study group was first asked to perform two concentration games where they were given two identical game boards on two tile screens. The concentration game was to match two identical cards in the board until all the cards were matched. The task was ended when both game boards found the matched pairs. In the information search and retrieval task, the group was asked to search on web sites using multiple web search engines to find answers to the questions. In the information visualization and exploration task, the group was asked to search for trends in a dataset to verify or refute the questions.

The first day consisted of a 1-hour training session to help the participants gain familiarity with the Continuum technologies, tasks, and basic concepts of correlation statistics and multivariate data analysis. After the training session, they were distributed in two Continuum spaces (with one keyboard and mouse control in each site) and they were asked to perform a set of collaborative tasks: two concentration games (15 minutes), three questions on the information search and retrieval task (45 minutes), and seven questions on the information visualization and analysis task (60 minutes). The group had a 10-minutes short break after the completion of each task and a 30-minute group interview session after the completion of all three tasks to rate the usability and general effectiveness of the Continuum technologies.

On the second day, all three participants were located in the same room with three keyboards and three mice (1 input control per person). The tasks given to the group were the same as on the first day, but the questions were more ambiguous and more negotiations were required than on the first day: two concentration games, one decision-making question on the information search and retrieval task, and five questions on the information visualization and analysis task. The interview session was followed shortly after the completion of all three tasks.

3.1.1 System Configurations

The top image on Figure 3 shows the distributed condition. Two of them were located in the same room and the third was alone in the adjacent room. The third participant was chosen to be the one who had some experience with the Continuum technologies to encourage active participation during the task. All of the participants could speak to each other via AG. The touch-screen whiteboard was connected via NetMeeting for shared note taking. The tiled displays (1 by 4 table mounted in

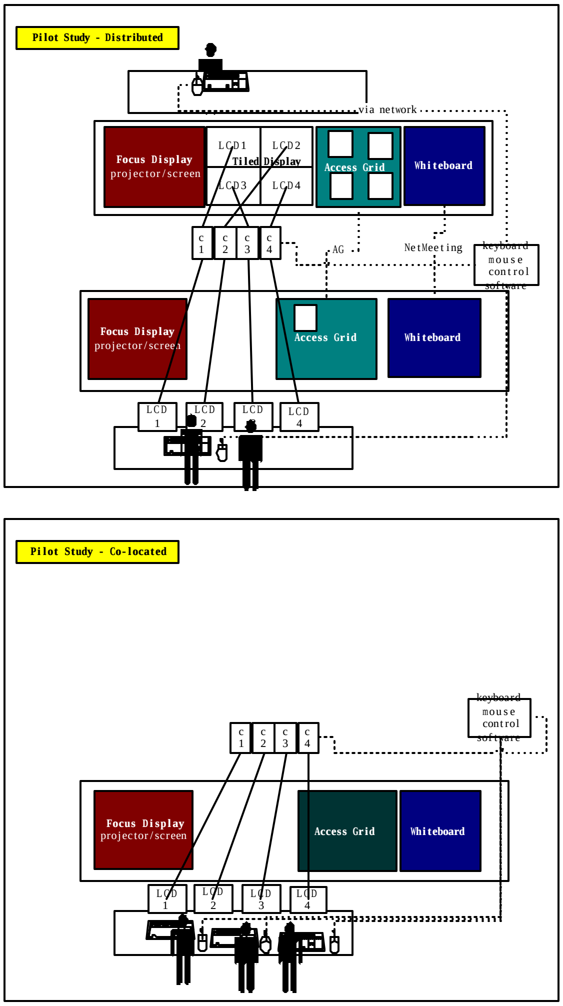

Figure 2. The diagram of system configurations on the pilot study. The top image shows the distributed condition (1 input per site) and the bottom one shows the co-located condition (1 input per person).

one site; 2 by 2 wall mounted in the other) were also shared between the two sites. The Switcher program [7] allowed anyone to grab the remote keyboard and mouse control for any of the tiled display screens. The Switcher used a VNC (Virtual Network Computing) server program on each tiled display cluster node and a VNC client program on laptop or tablet PCs. This program provides a way to quickly switch the input control from a laptop or tablet PC to any tiled display nodes. A projection display in both sites showed one of the tiled display screens in a large format. Only one keyboard and mouse was provided in each site, and hence the two co-located participants had to share one input control.

The bottom image on Figure 2 shows the co-located condition. All three participants worked side-by-side in front of the tiled displays (1 by 4 table mounted). Since the participants were co-located in the same room, we did not provide Access Grid or sharing capability on the whiteboard. Three keyboards and mouse input devices were provided for the subjects. Using Switcher, they could interact with any of the tiled displays.

3.1.2 *Observations*

We observed *a sense of ownership pattern* of three participants using the shared tiled display. The initial configuration of the Continuum allowed users to use any tile screens at any time, as well as allowed multiple users to interact with the same tile screen by social turn-taking protocols. However, participants tended to find and use different tiles for individual workspaces. This means everyone had visual access to all the workspaces, but owned input access to a particular workspace.

The tiled display offered *multiple individual workspaces* while maintaining necessary *awareness between distributed participants*. The tiled display was also useful when participants needed *multiple views and side-by-side comparison*. The projection display was used once or twice when they wanted to examine the patterns of dataset in a bigger format in the information visualization and exploration task. Similarly the shared touch screen whiteboard was used only for recording the answers as it was requested.

Furthermore, we observed participants tended to see various display technologies provided in the Continuum as *one big continuous display*. They expressed the desire to *move data from one display to another* (e.g. *cut-and-paste*) during the task. In fact, participants often informed one another to *transfer information (e.g. URL, findings, notes) between displays*. Initial observations also indicate the need for more *flexible and configurable tiled display* that can project up to single large high-resolution data visualization for the easy transition between individual work and group discussion.

3.2 The Iterative Design Studies

Based on the initial trial of the Continuum from the pilot study, we developed the iterative design studies. The goal was to determine which parts of the Continuum typically get used in a variety of tasks, to find out which technologies work or not, and to get user feedback on how to reconfigure the Continuum for these tasks. Then, we develop and examine a follow-up user study with new configuration of the Continuum display technologies.

A group of four students were placed in adjacent rooms in EVL and asked to perform a variety of information discovery and knowledge crystallization tasks using the Continuum technologies. The tasks were:

1. Information querying and gathering task – Participants were asked to search and gather information on the web to answer three questions. The questions were two focused questions where

participants would gather as many as findings on the web simultaneously to answer the question quickly and one overall trend question where they would focus on making a conclusion based on their collective and combined findings.

2. Information analysis and pattern detection task – Participants were asked to perform exploratory data analysis on a dataset using the XmdvTool information visualization system [24] to answer seven questions. The questions were five specific questions where participants would find evidence to verify or refute any of these hypotheses and two trend search questions where they would search for trends/patterns in the dataset.

3. Brainstorming and design task – Participants were asked to brainstorm, prioritize, and summarize design ideas for the Continuum technologies.

Two groups of four students participated in for each iterative design study and the questions given to the groups were different (either Question Set1 or Questions Set2). Our subjects were asked to participate in two studies and performed the tasks in two different orders (either Question1 and then Question2, or Question2 and then Question1). Question1 consisted of the Cuba sugar industry search and the Cereals dataset. Question2 consisted of the University search and the Boston housing dataset. The experimental design protocol showing the task and the group that is assigned for each iterative study is described in Table1.

In the first and second design study, the groups gathered in the same room and received a 1-hour training prior to the tasks. The training consisted of a description of the Continuum hardware/software technologies, then task instructions and basic concepts of correlation statistics and multivariate data analysis (such as scatter plot matrix and parallel coordinates) for information analysis and pattern detection task. After the training, the two pairs of subjects were distributed between the two Continuum spaces, and then asked to perform three collaborative tasks: information query and gathering task; information analysis and pattern detection task; and collaborative brainstorming and design task. The participants had a short break at the completion of each task and they were asked to answer the post-test questions to give us feedback about the usability of the Continuum technologies.

In the third and fourth study, the groups were re-organized so that new group was formed with two people from the two groups previously participated in the first and second study. For example, Group5 was formed with two people from the Group1 participants and two from the Group4 participants. We regrouped the participants to see if they broadened their ideas about the best way to use the technologies because we observed the groups used technologies in very different ways in the first and second study. Since the groups were already familiar with the technologies and the task, they just distributed in two Continuum spaces and performed the same set of collaborative tasks. At the end of the tasks, the 30-minutes debriefing interview session was followed.

We recorded audio and video of the groups using video cameras. Access Grid node operators helped in running the AG session between two rooms. A technical assistant was assigned to each room to resolve any problems that arose during the study. An evaluator in each room recorded group behaviors taken into the observation notes. The groups' activities (such as the history of visited web sites and XmdvTool usages) were captured into log data files.

Table 1. The experimental design protocol showing the task and the group that is assigned to the study. It's a two-tiered user study: subjects participated in two studies and received the order of either Question1 followed by Question2 or Question2 followed by Question1.

	Group A	**Group B**
The First Design Study	Group1 Training & Question1	Group2 Training & Question2
The Second Design Study	Group3 Training & Question2	Group4 Training & Question1
The Third Design Study	Group5 Question2	Group6 Question1
The Fourth Design Study	Group7 Question1	Group8 Question2

3.2.1 The First Design Study – Enhancing the Continuum to support the illusion of seamless displays

In the pilot study we observed the participants tended to see the various displays provided in the Continuum as one big continuous display, e.g., the desire to move data between displays during the task. That resulted in the development of SpaceGlider [1], a software interface that allows users with laptop or tablet computers to navigate across the display screens. A similar work is PointRight, a pointer/keyboard redirection among multiple displays [6], in the Interactive Workspace Project.

Two groups of four students were participated in the first design study. The groups received 1-hour training first. Then, the participants distributed in two separate sites

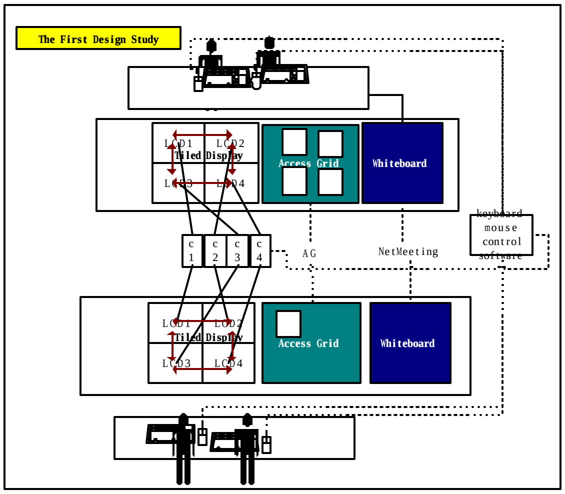

Figure 3. The diagram of system configurations on the first design study. SpaceGlider allowed users to move across the boundary of the tiled display. The arrow indicates the pointer transition path between displays.

and performed 2-hours collaborative problem solving tasks: 30 minutes of information querying and gathering, 45 minutes of information analysis and pattern detection, and 30 minutes of brainstorming and design task.

3.2.1.1 System Configurations

In this study, we tried to replicate the display setting as much as possible in both sites: the shared LCD tiled display (2 by 2 layout) on the left wall, AG plasma display in the middle (4 cameras and 2 microphones in full AG setting, and 1 camera and 1 microphone in mini-AG setting), the shared touch-screen whiteboard on the right, and 4 keyboards and mouse (1 input control for each user) SpaceGlider connecting 4 tiled screens. The projection display was not provided in this study because it was underutilized in the pilot study. (Figure 3)

3.2.1.2 Observations

Most of all participants wanted more microphones and cameras in mini-AG setting for the quick improvement of this configuration. They also wanted a remote site camera control that allowed positioning the remote site's cameras to the point of interest. The participants tended to think camera positions and angles were important. Among 4 different camera views, the remote collaborator's face view was the most important one. In fact two remotely located participants often gazed at the AG video windows during discussion over AG.

We frequently observed *collaboration between two participants to transfer data between displays via voice channel* (e.g. one read the text from the tiled display while the other wrote it down on the whiteboard). We call this pattern the read-and-write collaboration. Moreover, participants desired to *move the window from one display to another* (e.g. a person attempted to move a Netscape window to the collaborator's workspace) and *copy/cut and paste texts between displays*.

When using SpaceGlider, participants at first *had a trouble identifying each individual's mouse pointer* and *complained about conflicts between multiple mouse pointers* presented in the same screen at some points during the task. They suggested that we implement awareness tools such as allowing multiple mouse pointers with nametags or indicators for who is owned a certain screen.

While the shared tiled display seemed to encourage casual glancing over at the remote collaborator's workspace to see what they were doing, participants often checked about the task progress over the AG, e.g. *asking the remote collaborators which question they were working on*. Furthermore, we observed differences in group's working patterns, which invoked other design issues while using technology differently. The second group divided the task, and members mostly worked independently on individual tile screens and shared the answers on the whiteboard. This group had less conflicts of SpaceGlider mouse sharing on the tiled display, but they had greater *conflicts between remote participants on the shared whiteboard*.

3.2.2 The Second Design Study – Introducing TabletPC for individual input controls and Improving mini-AG setting

The first study showed users with SpaceGlider seemed to feel more continuity between the displays. The participants even attempted to move windows (e.g., Netscape) from one screen to another. However, the first study also revealed design problems in SpaceGlider, all concerning mouse sharing and identification.

Two groups went through the same procedure as the first study. The questions given to the two groups were the same as the first study, but in reversed order.

3.2.2.1 System Configurations

In the second study SpaceGlider connected the 4-node tiled display screens and the whiteboard. We increased the size of the mouse cursor on the tiled display for easy mouse identification, and gave each user a tablet PC for individual input control. On the mini-AG, we added another microphone and video camera, and a magnifying filter on the close-up camera to encourage casual interaction. (Figure 4)

3.2.2.2 Observations

We observed the same design problems again. Participants in the second design study also expressed the desire to cut-and-paste texts and to move the window between displays. Similarly, we observed the mouse

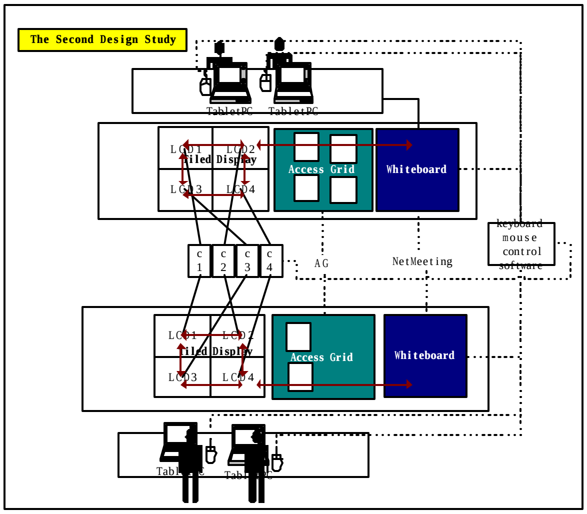

Figure 4. The diagram of system configurations on the second design study. SpaceGlider connected the 4-node tiled display and the whiteboard.

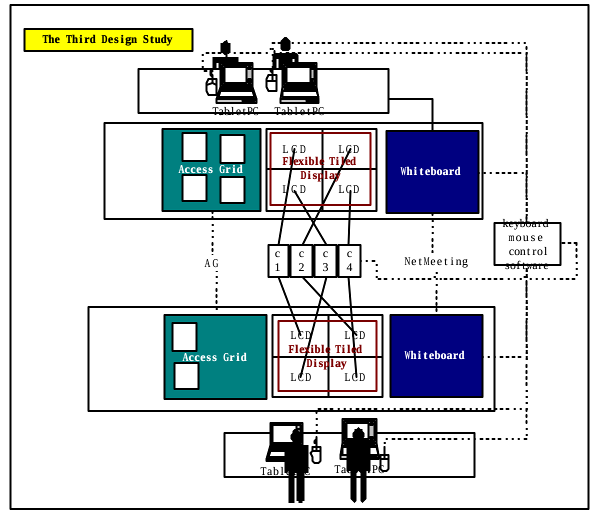

Figure 5. The diagram of system configurations on the third design study. Flexible tiled display allowed one of the individual workspace to be maximized over the entire tiled display for group discussion.

identification and conflict problem caused by using SpaceGlider and the task progress check over the AG.

The additional camera and microphone helped improve interaction between distributed participants. We observed more discussion between the two sites over the AG. Interestingly enough, both groups suggested reducing the video sources to a video of the collaborators and removing a video of the remote tiled display. We, however, observed a few incidents of their uses of the whiteboard view video to identify and resolve the whiteboard conflict problem. For example, a participant who was planning to use the whiteboard first checked this video to see if someone occupied the whiteboard, and then use the whiteboard if no one was using it.

The presence of TabletPC seemed to encourage users to the private workspaces (i.e. *TabletPC as individual workspace and tiled display as public group workspace*). It also resulted in reducing users' casual glancing over at other's workspace on the shared tiled display. However, when distributed participants worked together, they used the tiled display as a means to interact each other.

With SpaceGlider connecting the 4node tiled display screens and the whiteboard in each site, the groups reported they didn't feel *the continuity of the workspace* because the AG plasma panel display was located in between the tiled display and the whiteboard. Hence, they suggested swapping the location of the tiled display and the AG display so that there is continuity in the display layout when moving a mouse pointer across the tile display and the whiteboard.

3.2.3 The Third Design Study – Enhancing the Continuum to support the flexible shared workspace for easy transition between individual work and group work

Two groups formed from students who participated in two previous studies performed the same set of collaborative tasks with different questions than they did in the first study.

3.2.3.1 System Configurations

In the third study, the tiled display was modified to allow the group to view either four individual screens or one screen maximized over the entire tiled display. Any user could turn on or off a full-screen option (to make his/her workspace to be maximized over the entire tiled display) at any time. This flexible tiled display was implemented by using Aura [16, 17]. Each tiled screen had a distinct background color to identify each individual's workspace. Since the same SpaceGlider design problems presented in the second study, we provided Switcher for users to access the tiled display and the whiteboard. To improve the display layout, we swapped the location of AG and the tiled display so that the tiled display was centered and next to the whiteboard. (Figure 5)

3.2.3.2 Observations

Compared to the first and second study, we observed *more overhear/help/collaboration between distributed participants, fewer conflicts on the tiled display by using Switcher, and somewhat increased uses of the shared whiteboard*. More casual interaction between distributed participants may also be because of user's second time uses of the technologies and familiarity with the tasks. We

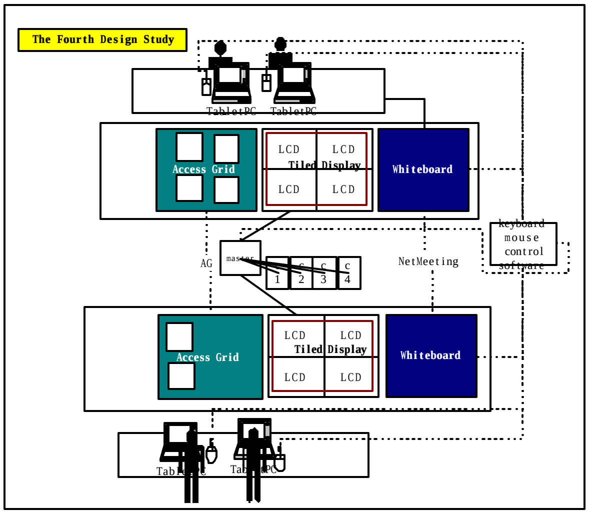

Figure 6. The diagram of system configurations on the fourth design study.

still observed *frequent notification of their plans for sharing resources and the task progress between distributed participants* (e.g. members spoke their plans out loud to confirm if they could use the whiteboard or not and to inform the progress of which question they have done and they were going to do next).

Both groups' pattern of technology usage was that members first assigned the individual workspace on the tiled display and shared their workspace with collaborators when it was needed (e.g. two of them used the same workspace together sometimes when one asked for help). Aside from copy and paste, trying to get the panels close together seemed to help a person transfer data between displays. There were *still some requests for copying and pasting*, particularly when a person tried to move fairly large texts from his/her workspace to the whiteboard. We still observed *read-and-write collaboration*, but *the desire to move the window from one display to another pattern was disappeared*.

One group used *the full screen option couple of times for group discussion (e.g. to present one's findings to others) as well as individual uses (e.g. for bigger scatter plot graphs)*. Since members of this group worked mostly on the TabletPC, the full-screen option did not interfere with others' ongoing work activities. The other group did not use this full-screen feature mainly due to the thick border of the tiled display.

Both groups preferred Switcher and the multiple colored individual workspaces against SpaceGlider, but they also stated that they would prefer SpaceGlider if a single user uses the system.

3.2.4 The Fourth Design Study – Evaluating a presentation model for the shared workspace

In the fourth study, we wanted to evaluate how a user's awareness of their remote collaborator's work factored into their combined problem solving ability. Hence, the tiled display was configured to a presentation model (i.e., sharing single individual workspace at a certain time on the tiled display). Two groups performed the same set of collaborative tasks with different questions.

3.2.4.1 System Configurations

With this configuration, members were assigned to their individual workspace on their tablet PCs and anyone could choose to show his/her workspace onto the tiled display so that all of them could see. They could show their individual workspace on the tiled display as either one full-screen large screen or four identical small screens. In addition, they could hide their workspace if they did not want to show it to others. Individual workspaces had the same distinct background colors given in the third study. This time participants were only allowed to switch between his/her own workspace and the whiteboard on the tablet PC. Besides the tiled display configuration, the other settings were the same as the third study. (Figure 6)

3.2.4.2 Observations

This configuration offered users with a private workspace but limited information sharing between them since it only allowed single individual's workspace visible on the tiled display. We also believed that it would disallow users' casual glancing over at collaborator's workspaces due to the same constraint.

In fact the most frequent behavior we observed was *the show me pattern* – e.g. one asked another to show your workspace or one informed the others to show my workspace. The groups tended to be less interactive over AG than the groups in the third study. A typical work pattern we noticed was two local members' working together and just informing the remote collaborators about answers or task progress.

Both groups wanted to see the four shared individual workspaces back on the tiled display as it was provided in the first and the second study. Some participants reported that *the tiled display was not useful this time and the different background color indicating individual workspace did not help either*. One group did not use a large full-screen on the tiled display, because of the thick border. The other group used full-screen few times for showing text in a bigger format, and this group reported that full-screen was used to grab remote user's attention.

4. DISCUSSION

This section will discuss some of important design issues based on observations in our iterative design studies.

4.1 Task Parallelism and Group Awareness

The work pattern was very different depending on task type and the group's working style. We observed the parallel work pattern mostly in the information querying and gathering task. All groups immediately started searching on the web to find the relevant information to the question. They worked independently most of their time and synchronized their findings with others from time to time. Some groups divided problems and worked independently on their individual workspace and shared the answers on the whiteboard, and then all of them worked together to make a decision towards the end. From the pilot study, we learned an input control must be provided per user in order to allow users to work in parallel. The pilot study group on the first day was hindered by fewer input controls during collaborative information search and retrieval – e.g. all of them wanted to search on the web independently but two co-located participants had to work together using one keyboard and mouse control.

Task parallelism can be seen by role division or division of labor. A previous study on collaborative information visualization [9] showed co-located pairs using Smart board tended to divide their labor into distinct roles of system user (who had the input control) and observer. In our collaborative information visualization, the pilot study group showed all of them working together pattern using one to four tile screens, where one person (acting as a system manipulator) controlled the mouse on the shared tiled display and rest of them (acting as reviewers) equally contributed to find the answers. Group1 and Group5 (referring to Table 1) also showed all four people working together pattern where mostly one person controlled the mouse on the shared tiled display (i.e. other three input controls were not used) and one person wrote answers down on the whiteboard. Most groups showed two local pairs working together pattern using two tiles per site (one in each site controlled the inputs). Some of these groups showed strictly divided labors (only answers were shared on the whiteboard), and some showed mix-mode collaboration where two pairs divided the problems but all worked together to verify the findings as well.

We observed several awareness issues in our distributed collaborative studies: mouse identification and conflict problem when using SpaceGlider, the shared whiteboard conflict and resolution, the task awareness problem. The group who solved the problems together sequentially had greater awareness of task progress. We observed the group who divided work between two sites did more informing or requesting their findings and task progress to their remote partners.

Participants could see the activity of others by glancing over at on the shared tiled display, though they didn't seem to pay too much attention to other's workspaces. However, we believe the fact that participants often used deictic reference (e.g. "this" or "that") and the fact that remote participants seemed to understand this reference easily is a result from participants' being aware of other's work through the fully visible shared tiled display. With the high quality AG video conferencing system, participants could overhear when problems arise, and help each other or work together on the shared tiled display even though they were remotely located. The lack of such awareness as shown in the fourth study (when the tiled display shared only one individual's workspace at a time) caused less interaction between remote collaborators and greater degree of explicit notification about findings, plans, and task progress between remote sites.

4.2 Videoconferencing Visual Cue

Most video conferencing systems provide only one or two views, typically showing collaborators' faces. Other approaches are head-mounted video systems that show views of worker's hands (i.e. camera focusing on active workspace) for collaborative physical tasks [3]. An Access Grid conference provides multiple simultaneous views of participants. Most AG nodes have three or more cameras and all cameras are displayed at all nodes participating in a conference.

One of our research interests in AG conferencing is to understand how to position the pan/tilt cameras and where to place video windows on the screens. In our iterative studies, we captured views of the overall room display layout (also capturing the spatiality of people in the room), the participant's front and close-up face, the tiled display area (capturing the participant's side and upper-torso and hand gestures on the tiled display), and the whiteboard area (capturing the participant's back and standing position on the whiteboard) in full-AG setting. The mini-AG camera was at first located in front of the AG screen and captured the side and upper torso view of the participants. We intended to capture their hand gestures on the shared tiled display to give visual cues of which workspaces is being addressed by whom. However, one immediate response was that the participants in full-AG setting requested changing the remote camera position to address the collaborators' face more directly.

As a result of the first design study, we therefore moved the camera in mini-AG setting to the top of AG screen and put a magnifying filter on the camera to capture the wide-angle, close-up, upper-torso view. We often observed *participants gazed at the video image of the remote participant close-up view during the course of a discussion*. We believed this collaborator's close-up view helped them get some forms of deictic reference or small feedback signal (e.g. nodding, murmuring, or facial expressions from the listener). After the first study, we also added one additional camera in mini-AG setting to capture the overall room display layout view. However, several subjects felt overwhelmed by the number of video sources and particularly a video of the tiled display did not help. The second study participants suggested reducing the video sources to a video of the collaborators even though they had used the additional video for whiteboard conflict resolution. Our participants at the interview in the third and fourth study reported that each individual used one or two videos but *all as a group used all the video sources*.

We observed some incidents of distributed participants using video images for identifying and resolving the conflicts in using the shared whiteboard. Group2 in the first study took longer to identify the whiteboard conflicts (due to NetMeeting whiteboard program disallowing the two simultaneous inputs) because they did not pay attention to the video of the whiteboard. Other groups who did pay attention to this video tended to reduce the whiteboard conflicts – for example, they checked this video to see if someone was using the whiteboard. We expected the participants to use video sources for preventing the whiteboard conflict, but they simply preferred to speak aloud about plan or status (e.g. "I'm going to use the whiteboard" or "I'm done using whiteboard"). This kind of discourse was observed largely in our study. This implies a need to develop the group awareness tool for the shared resources (such as a beep sound indicating someone's using the whiteboard) to reduce the number of conflicts and to increase the task-oriented interaction over AG.

4.3 Multi-Users Shared Input Control

We examined two legitimate ways of doing the navigation between tiles (and the whiteboard): SpaceGlider and Switcher. SpaceGlider has some obvious benefits for a single user and a large number of tiles in an amorphous configuration, but clearly it did not work in our multi-users shared case. Most groups were confused identifying an individual's mouse pointer at first and complained about accidental conflicts between multiple mouse pointers presented in the same screen. This result suggests *SpaceGlider needs to provide the multiple users' simultaneous input controls on all shared displays and the awareness tools such as nametags for mouse pointers or indicators for who is owned the certain screen*, to make it work for a multi-users distributed collaborative work.

We, however, believe the right turn-taking protocol would be sufficient for SpaceGlider in our shared workspaces model, rather than implementing the complex floor control that allows multiple users' simultaneous input controls on all shared displays. For the turn-taking protocol in a multi-users session on the shared tiled display, we think *a 'Give' protocol is more appropriate than a 'Take' protocol*. That way, users are not disturbed by the accidental intrusion of grabbing the remote control for the other's workspace while moving a mouse across the spaces. In a 'Give' protocol, the user with control of the shared workspace voluntarily relinquishes control, whereas in a 'Take' protocol, the user without control preemptively acquires control [5].

We observed a sense of ownership for the shared tiled display in the pilot study and the third study even though the participants could jump from tile to tile at any time using Switcher. This pattern may result from their natural use of social turn-taking protocols on the shared tiled display. In this configuration, the participants could see which tile screens were occupied on the fully visible shared tiled display, and hence they could quickly jump to another available tile for their individual workspaces. All participants preferred Switcher (used in the third and fourth study) to SpaceGlider (used in the first and second study) mainly because of fewer collisions between people for mouse sharing.

4.4 Private and Public Workspace

There have been studies conducted to understand the role of private and public workspaces in collaborative work [20, 22]. Their general conclusion was the system should support easy transition between individual work and group work. There were some approaches using multiple PDAs or tablet PCs as portable personal input devices for a shared public display. The Pebbles project [10] investigated the use of PDAs as a remote commander to allow users to send input simultaneously from PDAs to the same PC display as if they were using the PC's mouse and keyboard. Rekimoto's multiple device approach [14] demonstrated multiple users with Tablets as a personal tool palette to control a shared digital whiteboard in a collaborative setting. Users work on a personal tablet and then move the data onto a shared public computer (such as a digital whiteboard).

We investigated different configurations of the shared tiled display in our iterative design studies, and each resulted in showing slightly different group behaviors. The 2x2 wall mounted tiled display allowed the group to share their individual workspaces. This seemed to encourage group participants to casually glance over at others' workspaces. Tablet PCs as input devices for this shared tiled display seemed to introduce participants to the personal workspace (i.e. Tablet PC as a personal workspace and the tiled display as a public workspace) even though each TabletPC was identical to one of the tiled display. In this configuration, the groups mostly worked on the TabletPC and the tiled display was used mainly to work with remote partners or to check what remote partners were doing. It seemed the flexible tiled display with TabletPC supported easy transition between individual work (on TabletPC) and group-focused work (on the flexible tiled display). Finally, the groups were somewhat hindered by the presentation model of the tiled display. Perhaps, our collaborative task was benefits from immediate information sharing.

A pattern more related to the private and public workspaces was that some participants used a pen/paper or a text editor on the shared tiled display for taking personal notes during the task. While a paper note was kept as private, a text editor could become a shared notepad where distributed participants shared it for a discussion. There were some tensions between privacy and information sharing. Our display rich environments did not support privacy because information was always fully visible to all members. Interestingly, the participants in general appreciated having more awareness of collaborator's work through the shared tiled display, but some of them still wanted to have more of a private workspace for more focused work and personal uses (e.g. email). Further study is needed to explore the supports for private workspaces in concert with the public displays.

4.5 Display-rich Environment User Interface

Our participants consistently requested a desire to cut-and-paste text or move a window (e.g. Netscape browser) between displays. Moreover, we often observed participants physically moved between two displays or two participants worked together to read-and-write texts from one display (e.g. the tiled display) to another (e.g. the whiteboard). Participants used various channels (e.g. papers, Tablets, ftp, or verbal channel) for transferring data between displays.

Prior research in multi-device, multi-users interfaces has supported moving data between different displays. Examples include I-LAND's Take-and-Put protocol [21], Interactive Workspace Project's Drag-and-Drop protocol, and Rekimoto's Hyperdragging [15] or Pick-and-Drop protocol [14]. In our study, aside from cut-and-paste, we found it valuable to put the displays closer together, for easy data transfer between displays.

5. CONCLUSIONS

In this paper, we present the Continuum display rich project room designed for real-time distributed intensive collaboration and iterative design studies with the variations of the Continuum technology configurations. The study involves placing a group of collaborators in two separate Continuum spaces and asking them to perform a number of typical scientific tasks: information querying and gathering, information analysis and pattern detection, and collaborative brainstorming and design.

The quality of group performance was improved progressively from the first study to the third study as the system configurations for each study addressed the awareness and collaboration needs for a group. Additional camera and microphone in mini-AG setting helped increase more natural interaction between distributed participants, such as overhearing and using multiple video sources to see status of remote participants. Mirroring of tile screens to portable personal displays (Tablet PCs) provided users a close-up view of the tiled display, where users worked mostly on this personal workspace and used the tiled display for group discussion. Switcher input control reduced collisions between multiple users on the shared tiled display. The flexible tiled display seemed to be good for supporting both shared individual workspaces and a group-focused workspace (in the bigger format). Having experienced the shared tiled display, users really hated going back to classical power-point presentation model of collaboration, and they wanted more data side-by-side. Also, group performance was somewhat degraded by the extra step required to show individual private works to the group on the public display.

Our iterative design studies showed participants would take advantage of multiple display screens when given the opportunity. The tiled display as a large distributed corkboard seemed to encourage opportunistic interaction and collaboration between distributed participants. This configuration also helped alleviate some of the awareness problems associated with distributed teamwork by allowing group members to casually glance over at the other's workspace and by supporting information always visible to all the members. Our participants also showed using the tiled display for multiple linked views and side-by-side comparison. We believe the study also raised some important design issues to support display-rich environments for collaborative work. Examples are tools to move data from one display to another, flexible tiled display for easy transition between shared individual workspaces and group discussion, tools to support multiple users simultaneous inputs or to avoid conflicts, and tools to support maintaining awareness of group's task progress (like a history on a shared group web browser). We are currently implementing SpaceGlider to include cut-and-paste images/texts and awareness features such as nametags for participants' mouse pointers and indicators to show the shared resource ownership.

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