Design Considerations for Collaborative Information Workspaces in Multi-Display Environments

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Abstract—The incorporation of massive amounts of data from different sources is a challenging task for the conception of any information visualization system. Especially the data heterogeneity often makes it necessary to include people from multiple domains with various fields of expertise. Hence, the inclusion of multiple users in a collaborative data analysis process introduces a whole new challenge for the design and conception of visualization applications. Using a multi-display environment to support co-located collaborative work seems to be a natural next step. However, adapting common visualization systems to multi-display environments poses several challenges.

We have come up with a number of design considerations for employing multiple-view visualizations in collaborative multi-display environments: *adaptations of the visualization* depending on display factors and user preferences, *interaction techniques* to facilitate information sharing and to guide the users' attention to relevant items in the environment, and *the design of a flexible working environment*, adjustable to varying group sizes and specific tasks.

Motivated by these considerations we propose a system relying on a spatial model of the environment as its main information source. We argue that the system design should be separated into basic multi-display environment functionality, such as multiple input handling and the management of the physical displays, and higher level functionality provided by the visualization system. An API offered by the multi-display framework thereby provides the necessary information about the environment and users to the visualization system.

1 INTRODUCTION

Modern information workers need to explore large information spaces to reach crucial decisions, such as those with strong influences on people's well-beings. Those decisions are rarely made by a single person but are rather discussed and evaluated by a team of experts. Examples are doctors deciding for treatment courses after exploring and discussing the diagnostic data of patients, architects and other stakeholders discussing on urban planning issues [15], emergency services having to react to ongoing crises, scientist discussing patterns and findings in data, or engineers collaborating with their peers when designing the car of the next generation. All these scenarios are accomplished by a small group of experts and involve massive amounts of data.

Information visualization software helps to cope with large amounts of data by letting the user interactively explore the information space. Especially multiple-view visualization can prove useful in collaborative information analysis situations, where users might prefer different visualization styles based on their personal preferences and knowledge backgrounds. However, most software solutions have two major shortcomings impeding effective collaborative work: First, they are designed as single-user applications not able to distinguish input from multiple users, even if the underlying operating system is capable of handling multiple input devices. Second, single-machine software has to cope with limited screen space, typically a single or dual monitor setup.

It seems natural to match the multiplicity of displays in a multi-display environment (MDE) to the multiplicity of users and visualization views in a multiple-view visualization system. MDEs combine displays of various form factors to a unified interaction space. Traditional collaboration in small groups, where participants discuss print-outs on a table, take notes in private notebooks, and sketch ideas on a white board, can be emulated by turning unused wall and table spaces into interactive workspaces and integrating brought-in personal devices into the interactive environment.

Building a visualization system that makes optimal use of an MDE is not simply a question of providing a very large number of pixels. Collaboration requires that users can manipulate application content simultaneously and tailored to their personal preferences, and that tools for guiding the users' attention in the large workspace are provided. Visualization styles, placements, and detail-levels should differ depending on the used display and the users interacting with the visualization. Tasks such as choosing the appropriate display for a visualization or the appropriate level of detail of a visualization for a particular display can be solved manually. However, we believe that an automated approach can facilitate the usefulness of such systems. To automate these operations the system requires knowledge of the geometric and topological properties of the display setup, the locations of the users within the environment, and their backgrounds and preferences.

(a) (b)

Fig. 1. Examples for collaborative information analysis in multi-display environments: (a) analysis of biomolecular data and (b) urban planning.

In this paper we present a set of design considerations for visualization and interaction techniques tailored to collaborative multi-display situations, as illustrated in Figure 1. Subsequently, we will propose a system design for a co-located collaborative information workspace incorporating multiple displays of varying form factors. We will show that the system's detailed knowledge of spatial display arrangements and user locations is crucial when building collaborative information workspaces in MDEs.

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2 Related work

In their "rule of diversity", Baldonado et al. [1] suggest that multiple views should be employed if users' preferences and knowledge backgrounds differ. Convertino et al. [4] proposed a single team view and role-specific private views for each team member to ease the group analysis task of a map-based visualization. Tang et al. [20], as well as Forlines and Shen [6] demonstrated systems providing each user with tools for filtering a single, shared view. Isenberg et al. created a collaborative visualization system for a multi-touch table [9]. They also presented a set of design guidelines for collaborative information visualization systems, which was extended by Heer et al. [8]. Our design considerations differ, as we are more focused on MDEs with special emphasis on the influence of display geometries, display topologies, user locations and user preferences on the visualizations.

In an MDE, Forlines and Lilien [5] distributed multiple coordinated 3D views of a protein to an interactive touch display, two wall displays, and a tablet PC for fine-grained interaction. Although their system supports multiple users by facilitating a multi-touch table, they do not provide special collaborative interaction features. Shen et al. [16] developed a taxonomy of multiple-view visualization styles in multi-display environments . They proposed three visualization styles differing in their synchronization method. In contrast to their taxonomy, we propose the separation of the system into a multi-display framework and a visualization framework to not limit the MDE's functionality to the visualization system and likewise, not to limit the visualization system's applicability to the specific MDE.

3 Design Considerations

Special requirements for co-located collaborative information visualization systems arise from the implicit components: *multiple users* are operating on *multiple data sets* by using *multiple visualizations* on *multiple displays*. A discussion of the requirements in terms of visualization and interaction is followed by considerations about the needed properties of a multi-display environment supporting co-located information seeking.

3.1 Visualization Techniques

In a collaborative MDE, not only inherent display factors (i.e., the display geometries) have an influence on the subjective quality and perceptibility of the visualization. The users' preferences and knowledge backgrounds play an equally important role.

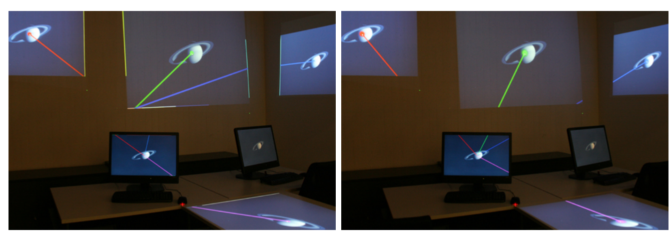
Visualization LOD: The visualization's level of detail should vary with the display. Display parameters, such as size, resolution, distance to the users, and viewing angles of the users, influence the required or possible level of detail a visualization can show. The level of detail adjustment depends on the view, but generally affects the level of abstraction, the number of text labels, the size of the remaining text labels, and how much data entities are shown in the view. If the number of available pixels does not allow a visualization to show all data entities simultaneously, abstractions such as clustering or focus+context methods can be applied to convey an acceptable compromise between overview and detail. As an example, consider a low-resolution wall projection serving as contextual information space, while users conduct individual work on their private workstations. The local visualizations on the private displays show a large number of elements in a plot, while context views on the wall show only contextually relevant elements.

Personalized views: The visualization's level of detail should vary with the user. Experts from different domains might not only prefer different data representations, but also specific terminology. When reviewing data collaboratively, a shared information space easily gets cluttered with extensive text labels and alternative representations. In an MDE, private monitors provide a convenient space for visualizations adjusted to the users' background and preferences without affecting shared or other users' private views. We hypothesize that users prefer more sophisticated and interactive views on private displays, while views, which require less precise interaction and convey information in a more obvious way, are preferred on shared display spaces. In addition, visualizations on public displays can combine information from different data domains and therefore bridge the knowledge gaps between experts from different fields, as explained in a companion paper by Streit et al. [19]. However, we believe that it is crucial that the user retains control over which information should be visible on which display.

3.2 Interaction Techniques

Typical activities when using information visualization systems include interactive filtering [17] and brushing [10] to understand the data and its relations. These actions are equally important in a collaborative multi-display setting, but there are some issues which have to be considered: First, multiple discontinuous display spaces make relating linked elements and arranging the multiple views more difficult. Second, having multiple users frequently shifting between a loosely coupled and a tightly coupled work style [7, 20] poses challenges to make these shifts fluid, while preserving sufficient privacy for undisturbed individual work.

Visual Linking: Guide the users' attention. When information is scattered in an MDE, relevant items, for instance data elements related to the user's current selection, might not be in the user's direct field of view. Subtle highlighting of related elements might not be sufficient to guide the user's attention to secluded display spaces. An approach to show relationships between items more explicitly is visual linking [3], which draws line connections between related elements in two views. However, in an MDE the visual links between views need to bridge display space potentially covered by other applications, as well as display-less space between two adjacent displays. The path across discontinuous displays becomes ambiguous as soon as the displays are not located on the same depth level. Figure 2 shows two possibilities how to design cross-display visual links: A static determination of entry- and exit points for lines connecting two screens makes the visual links predictable and works equally well from every perspective (Figure 2a). When drawing visual links from a single user's perspective, the complexity for the user is reduced (Figure 2b), while other users perceive discontinuities in the links.



(a) (b)

Fig. 2. Visual links demonstrating the shortest navigation paths from the current mouse pointer location to potential target displays to ease navigation in an MDE: (a) through static entry- and exit points, and (b) by incorporating user perspective.

View relocation: Provide semi-automatic mechanisms to share information. Especially when working in an MDE with private monitors hidden from other participants, there are several situations where users would like to move visualizations from one display to another: They may want to retrieve a copy of a public visualization view for detailed investigation on their private workstations, they may want to send a copy or reference of their visualization directly to a single collaborator or to a group of collaborators for discussion, or they could also place visualization views on a public display space without the intention to immediately discuss or present findings. Moving objects (e.g. visualization views or application windows) across display boundaries using interaction techniques like drag and drop [13, 11] is a non-trivial task, especially if the display topology is complex and user interaction can potentially interfere with other participants. However, with the system's knowledge of display arrangements and user locations, we can provide high-level interaction techniques like *pub-*

lish, *deposit*, or *obtain* which intelligently move views to displays. For example, users wanting to discuss findings identified on their private workstations, press a *publish* button in the graphical user interface. The system then identifies the most suitable target display by considering properties of the visualization (*Can the level of detail be adjusted? Does it contain rotation-sensitive elements?*) and the potential target displays (*Is it visible for all affected users? Is there someone interacting with the display?*). The view is then relocated to the best suited display. To allow for manual adjustment, conventional drag and drop relocation techniques should additionally be supported.

Privacy: Ensure uninterrupted individual work. Linking & brushing assures that selections made in one visualization are reflected by all other views. For instance, if a user selects an element in one view, this event can modify all other views in the environment – shared views, as well as views on private display spaces. If other participants' private views are modified in a loosely coupled collaboration situation, their ongoing activities might get interrupted. The system thus needs to treat views placed on private display spaces with special care. Linking & brushing events for private views need to be restricted to avoid sudden, unexpected changes interrupting individual work. Likewise, visual links should not connect elements between shared views and private views, unless invoked by the owner of the private view.

Personalized Interaction: Make individuals' actions distinquishable. Personalized interaction techniques, for example user-based color-coding visual links and highlights, helps users to distinguish actions from different collaborators. System responses tailored to the users' preferences (e.g. by providing customized mouse-over information [14]) are especially important when experts from different domains collaborate. Such features require a system capable of distinguishing input from multiple users.

3.3 Environment

In an MDE, the working environment can be tailored to the information analysis task to be accomplished and the group being involved. This affects the physical display arrangements as well as the display form factors. Additionally, the users should be able to customize their system by freely choosing their supportive software tools.

Display setup: Make the display environment (re-)configurable. By mixing displays of varying affordances, collaborative tasks can be simplified. For instance, people can gather around a tabletop display to discuss information, while a wall display is used for presentation purposes. Private displays introduce an implicit task separation and foster a loosely coupled work-style. An MDE has to be carefully designed to find the perfect balance between providing sufficient display space, arranged in a fashion to best support the group activities, while not overwhelming the users with a seemingly endless amount of visible information. A collaborative information workspace has to accommodate for these situations by being adjustable to task requirements and group size. It should be easily reconfigurable to support a changing group size and to incorporate brought-in mobile devices, such as personal laptops.

Display geometry: Make the displays configurable. For detail-rich visualization representations, it is not only important to provide high-resolution displays. In certain cases, visualizations can benefit from unconventional displays in terms of aspect ratio or display geometry. Consider, for instance, the parallel coordinates visualization shown in Figure 3: With limited screen space, horizontal scrolling or panning is required to explore all dimensions. By combining multiple projectors to a very wide, high-resolution projected display, even degenerated visualizations with aspect ratios not conform with conventional monitor dimensions can be explored without scrolling, panning, or zooming.

Application Transparency: Provide supportive applications. A collaborative information analysis session clearly benefits from a rich visualization system support such as cross-machine linking & brushing. However, conventional software tools, such as web browsers, e-mail clients, or presentations tools can further enrich the collaborative session. It is therefore important to also allow legacy applications to function as usual in such a setup.

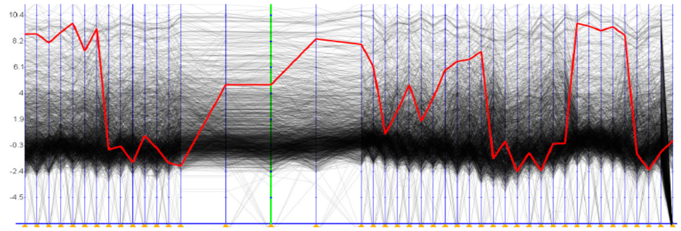


Fig. 3. On a conventional monitor showing all dimensions of this parallel coordinates view would result in visual clutter, due to the limited space between the axis. On a very wide horizontal display more dimensions can be visualized simultaneously with sufficient spacing.

4 System Design

Based on the design considerations discussed above we propose a system design that includes a detailed spatial model of the environment as its main information source. As shown in Table 1, many of the visualization and interaction techniques proposed cannot be provided without knowledge of geometric display properties, the display topology (i.e., the spatial relationship of displays to each other), and the location of the user within the environment with respect to the display locations. However, the spatial model is not only necessary for visualization and interaction techniques, but is also required to build a flexible, configurable display environment. The aforementioned displays with unconventional aspect ratios and geometries can be built from multiple casually aligned projectors or projections onto non-planar surfaces, using geometric compensation and edge blending (see [2] for an overview on seamless multi-projector displays).

	Display geometry	Display topology	User locations	User preferences
Visualization LOD	x		x	(x)
Personalized views				x
Visual linking		x	(x)	
View relocation	x	(x)	x	
Privacy		x	x	x
Personalized interaction			x	x

Table 1. Information sources required to provide display- and user-adaptive visualization and interaction techniques.

At our institute, we have developed *Deskotheque* [12], a distributed multi-display framework which acquires a three-dimensional model of the environment in a camera-assisted offline calibration step. Figure 4 shows a multi-display setup coordinated by the Deskotheque framework and the corresponding spatial model. Based on this model, we derive geometric compensation and edge blending for projected displays to support the construction of large high-resolution displays from multiple projectors and projections on multi-planar surfaces. Geometric compensation is applied in a 3D compositing window manager, thus transparent to any applications run in the environment [21]. From the spatial model we can also roughly estimate user locations, by assuming the users to be located at a static distance in front of a personal workstation monitor. This information is employed for providing spatially consistent cross-display mouse pointer navigation, which is crucial to access all display spaces in an intuitive fashion.

As Deskotheque is designed in an application-transparent manner, any information visualization application can be operated on the MDE framework without further adaptations (c.f. Figure 1a). However, to implement all the design considerations discussed in the previous sections, knowledge about the environment is required by the visualization application. We are therefore currently working on extending *Caleydo* [18], a multiple-view visualization system from the biomedical domain developed at our institute, to a distributed system which will make use of information provided by *Deskotheque*.

We anticipate a clear separation of MDE- and visualization framework. The multi-display framework has to provide the basic technology to create a shared workspace – irrespective of the anticipated con-

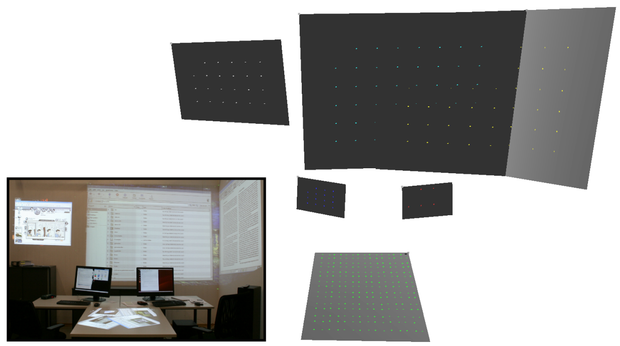


Fig. 4. The spatial model of a multi-display environment. Mind that the right multi-planar wall display is composed of two overlapping projections and all projected displays are geometrically compensated for projective distortion.

tent. This includes – but is not limited to – geometric compensation of projected displays, cross-display mouse pointer navigation, multiple input support, and object relocation facilities on window level, as well as the creation and maintenance of the spatial model of the environment. The visualization framework keeps records of user profiles and is responsible to provide appropriate visualizations adapted to display factors and user preferences. It also has to take care that multiple views distributed on multiple displays, and machines respectively, are synchronized and events are forwarded to all instances.

To adapt the visualization style, to calculate automatic placement positions, and to distinguish multiple collaborators, it can rely on an API exposed by the MDE framework which provides access to the display geometries, arrangements, user locations, and users associated with input events received by the visualization framework. The MDE framework furthermore has to take care to provide interfaces for cross-display painting of visual links (c.f. Figure 2), which is accomplished by a window manager plugin.

5 Conclusion

With increasing power and popularity of projectors and large-scale monitors, as well as the availability of massive amounts of data, extending visualization systems to MDEs seems to be a logical step. In this position paper we have presented a set of design considerations for adopting visualization and interaction techniques to this new situation and for what the environment for a collaborative information workspace should look like. Based on these, we have proposed a system design for such an information workspace with a clear separation between multi-display- and visualization framework. As a major requirement for a collaborative information workspace we have hypothesized the availability of a spatial model of the environment, describing the individual displays' geometries, the display topology, and the location of the users within this environment. Only with this knowledge we believe that the system can sufficiently support the users in their collaborative analysis task by adapting visualizations to the display form factors, providing highly sophisticated interaction techniques, and guiding their attention to relevant information.

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