

Interactive Tree Comparison for Co-located Collaborative Information Visualization

Petra Isenberg and Sheelagh Carpendale

Abstract—In many domains, increased collaboration has led to more innovation by fostering the sharing of knowledge, skills, and ideas. Shared analysis of information visualizations does not only lead to increased information processing power, but team members can also share, negotiate, and discuss their views and interpretations on a dataset and contribute unique perspectives on a given problem. Designing technologies to support collaboration around information visualizations poses special challenges and relatively few systems have been designed. We focus on supporting small groups collaborating around information visualizations in a co-located setting, using a shared interactive tabletop display. We introduce an analysis of challenges and requirements for the design of co-located collaborative information visualization systems. We then present a new system that facilitates hierarchical data comparison tasks for this type of collaborative work. Our system supports multi-user input, shared and individual views on the hierarchical data visualization, flexible use of representations, and flexible workspace organization to facilitate group work around visualizations.

Index Terms—Information visualization, collaboration, co-located work, hierarchical data comparison.

1 INTRODUCTION

It is common for small groups to gather around information that often involves some sort of visualization. Imagine a team of medical practitioners (doctors, nurses, physiotherapist, social workers) examining a patient's medical record to create a discharge plan, a team of geologists gathering around a large map to plan an upcoming expedition, or a team of executives looking at charts showing the latest sales trends. In many disciplines, collaboration allows for a multi-disciplinary group with an increased skill set. Different team members offer different perspectives and expertise that together can improve the quality of the solutions. Analyzing data collaboratively can also have several benefits. For instance, the information space may simply be too complex for an individual to interpret in its entirety, or the dataset may be susceptible to a variety of interpretations, in which case experts may discuss and negotiate their interpretations of the data. With large data sets, even the task load of *exploring* the data could be shared among several individuals on a team [33]. The benefits that collaboration offers to this process have motivated us to shift our efforts from single-user information visualization tools toward the design of *collaborative* information visualization tools.

Current information visualizations have mostly been designed from a single-user perspective. While it is possible for small teams to work with information visualizations using the standard setup of a small screen, one mouse and one keyboard, only one person at a time is able to make any changes to the view of the system. Attempting to collaborate under these conditions can be awkward and unnatural. The recent trend toward the use of large interactive displays offers the potential for the development of improved collaborative information visualization systems in which many co-located users can simultaneously interact and explore data sets. However, it is not yet understood how interfaces, visualizations, and interaction techniques should be designed to specifically address the needs of small co-located groups. The research problem we address is that, while most information visualization tools support sophisticated interaction with data, they have only limited facilities to support the collaborative activity of a team [14].

Research into supporting computer-supported cooperative work

- Petra Isenberg is with the University of Calgary, E-mail: pneumann@cpsc.ucalgary.ca.
- Sheelagh Carpendale is with the University of Calgary, E-mail: sheelagh@cpsc.ucalgary.ca.

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(CSCW) has considered both collaborations across distances (distributed) and collaborations where the team shares the same workspace (co-located) [12]. In our research, we focus on co-located collaboration. We present a collaborative information visualization system that supports collaborative analysis of data for small groups as they gather around an interactive digital table. Hierarchical data visualizations can be explored and compared in our environment through the use of several features that have been designed to facilitate collaborative work practices: multi-user input, shared and individual views on the hierarchical data visualization, flexible use of representations, and flexible workspace organization.

Our main contributions are: an analysis of challenges and requirements for the design of co-located collaborative information visualizations and a visualization system for collaborative tree comparison tasks around a large multi-touch tabletop display.

2 RELATED WORK

We start by reviewing the relatively small body of research that is directly concerned with the problem of supporting collaborative work around visual information. Then we consider research in the synchronous and asynchronous distributed domains, followed by a discussion of the work that focuses on supporting group analysis of visualizations in a shared space. Lastly, we discuss related work in the area of hierarchical data comparison to lay a foundation for our collaborative visualization system.

2.1 Collaborative Information Visualization

Research on the *process* of collaborative data analysis using information visualizations is relatively scarce. Mark *et al.* [14, 15] conducted a user study in which they observed pairs working in co-located and distributed settings with two different visualization systems designed for single users. Their findings suggest that the benefit of collaborative vs. individual problem solving was heavily dependent on the visualization system used and also that, in general, groups were better at locating errors [15]. In their second paper, Mark *et al.* [14] introduce a model for the collaborative problem-solving process. The model consists of an iterative sequence of five stages: parsing a question, mapping variables to the program, finding the correct visualization, and two validation stages. For collaborative work on scientific visualizations in virtual environments using CAVEs, Park *et al.* [20] report a five-step activity model that was common for the observed collaboration sessions. Their study also noted that participants showed a strong tendency for independent work, if the option was available.

2.1.1 Distributed Visualization Systems

In the area of scientific visualization, distributed systems have been introduced as early as 1994 [1] (see [6] for an overview). Less research has focused on distributed collaborative systems more directly concerned with *information visualization*. CoMotion is a collaborative environment for creating information analysis and decision-support applications [16]. The application provides shared views of the data on which all users can *synchronously* interact. The Command Post of the Future is a visualization tool built on this architecture in which distributed team members can share visualizations of natural emergencies and combat situations [3]. Examples of web-based *asynchronous* collaborative environments include sense.us [9], Many Eyes,¹ and Swivel.² They all allow collaborative sharing and exploration of data by letting users upload and visualize data as well as comment on created visualizations. DecisionSite Posters [17], another web-based system for asynchronous collaborative work around information visualization, allows users to publish visualization results, descriptions, and data to distributed collaborators in interactive web-based reports.

2.1.2 Co-located Visualization Systems

The responsive workbench was one of the first visualization systems for co-located collaboration around a large horizontal surface [37]. The responsive workbench is a virtual reality environment in which the displayed 3D scene is looked at through shuttered glasses. Several scientific visualization applications were developed for this platform including fluid dynamics and situational awareness applications.

With a focus on interaction, radial tree layouts have been studied for collaborative circular tabletop systems [35]. In their system, Vernier *et al.* provide two different fisheye mechanisms to support different types of user activity around the tabletop. Interactive focus+context techniques for collaborative systems have further been applied in the DTLens system [4]. In general, no guidelines, as of yet, exist for the development of collaborative systems specifically tailored for information visualization applications.

2.2 Hierarchical Data Comparison Systems

The work most closely related to our approach is the TreeJuxtaposer system by Munzner *et al.* [18]. In this work, structural comparison of nodes is facilitated by finding the most similar (or best corresponding node) to one tree in another tree. The best corresponding node(s) and dissimilar nodes are highlighted in their system, giving an overview of structural differences and similarities between trees. Graham and Kennedy [5] present a system for linked highlighting across several hierarchies. Similarities are shown by giving similar nodes new degree-of-interest values leading to a more prominent display in the hierarchy. We chose to use the similarity measure as described in [18] to calculate similarities across our hierarchies. Our system extends comparative possibilities by incorporating collaborative comparative interactions.

3 DESIGN GUIDELINES FOR CO-LOCATED COLLABORATIVE INFORMATION VISUALIZATION SYSTEMS

In this section we discuss design guidelines specifically for *co-located collaborative information visualization systems*. These design heuristics are condensed from information visualization design advice [29, 38, 39, 40], co-located collaboration advice [8, 13, 23, 21, 24, 25, 26, 27, 28, 32], studies that look directly at collaborative visualization [14, 15, 20], and our observations of teams of people collaborating to solve tasks using information visualizations [19]. Other design heuristics exist that can guide the developer of an information visualization system in terms of the data domain, cognitive levels based on knowledge and task, or perception and cognition [41]. In the field of computer supported collaborative work (CSCW) a set of main design guidelines has been established for collaborative systems in general (e. g., [21, 28]); however, they do not take the specific problems and requirements of information visualization applications into account. Our intention is that these design guidelines, compiled from three bodies

of research, will form a basis which will adjust and expand as research in collaboration around information visualizations continues.

3.1 Hardware and System Setup

In this section we consider guidelines for the design of the physical workspace in which the collaborative activities around information visualization can take place.

Size: In information visualization, the size of the available display space has always been problematic for the representation of large datasets (e. g., [18]). In a common desktop environment, typically a single user will use all available screen space to display their visualization and, most commonly, this space will not be sufficient. Frequently, visualization software will include interactive features to help the user cope with limited display space. It seems sensible to think that, if we are going to adequately support collaborative or team exploration of visualizations, available display space will be an important issue. In collaborative systems, screen space has not only to be large enough for the required information display, it might also have to be viewed and shared by several users. As the number of people using a shared information display grows, *the size of the display and workspace needs to be increased* in order to provide a large enough viewing and interaction area that gives adequate access to all group members.

Configuration: Several configuration possibilities exist that could enlarge an information display, all of which will affect the type of visualization system possible and the type of collaboration work that would be most readily supported. Many types of configurations are possible; for instance, one could provide team members with interconnected individual displays, as in the ConnecTable system [31], or one could make use of large, interactive, single-display technology, like display walls or interactive tabletop displays (e. g., [32]). An additional possibility is to link wall, table, and personal displays (e. g., [38]), or to consider immersive displays (e. g., [20]). The type of setup most appropriate for an information visualization system will depend on the specific task and group setup. For example, individual interconnected displays allow for private views of at least parts of the data which might be required if data access is restricted. Tabletop displays have been found to encourage group members to work together in more cohesive ways, whereas wall displays are beneficial if information has to be discussed with a larger group of people [24].

Input: In the common desktop setup, input is provided for one person through keyboard and mouse. To support collaboration, ideally, each person would have at least one means of input. In addition, it would be helpful if this input was identifiable, making it possible to personalize system responses. If a collaborative system allows for multi-user input, the access to a shared visualization and data set has to be coordinated. Also, synchronous interactions on a single representation may require the design and implementation of new types of multi-focus visualizations. Ryall *et al.* [25] have addressed the problem of personalization of parameter changes for widget design. Based on user identity, their widgets can be dynamically adapted for individuals within a group. Similar ideas could be implemented for personalization of information visualizations during collaborative work.

Resolution: Resolution is an issue both for the output (the display) and for the input. The display resolution also has a great influence on the legibility of information visualizations. Large display technology currently often suffers from relatively low display resolution so that visualizations might have to be re-designed if readability of text, color, and size is affected by display resolution. Large interactive displays are often operated using fingers or pens which have a rather low input resolution. Since information visualizations often display large data sets with many relatively small items, the question of how to select these small items using low input resolution techniques becomes an additional challenge that needs special attention [11].

Interactive response: Implementations of collaborative information visualizations have to be carefully designed for efficiency. Individual information displays can already be computationally intensive and require considerable pre-processing (e. g., [18]). Yet, in collaborative

¹<http://services.alphaworks.ibm.com/manyeyes/home/>

²<http://www.swivel.com/>

systems several information visualizations might have to be displayed and interacted with at the same time. While powerful hardware can solve the problem to some extent, efficient data processing as well as fast rendering of the graphical representations should be considered when the needs of several users have to be addressed.

3.2 Designing the Information Visualization

Many known information visualization guidelines will still apply for the design of information visualizations for large displays or collaborative use (e. g., [2, 34, 36]). In this section we discuss additional aspects that need to be considered for the design of information visualizations for collaborative settings.

Supporting Mental Models: It has been shown that providing capabilities to freely move interface items is critical for group interactions and task coordination during co-located collaborative work [26]. Letting users impose their own organization on items in the workspace may help collaborators *create and maintain mental models* of a dataset that contains several different representations. By freely moving representations, team members can impose their own *categorizations* on the representations by, for example, placing them in close proximity or in piles relevant to a task.

Representation Changes: Zhang and Norman [40] found that providing different representations of the same information to individuals provides different task efficiencies, task complexities, and changes decision-making strategies. In a collaborative situation, group members might have different preferences or conventions that favour a certain type of representation. Gutwin and Greenberg [8] have discussed how different representations of the workspace affect group work in a distributed setting. They point out that providing multiple representations can aid the individual but can restrict how the group can communicate about the objects in the workspace. This extends to co-located settings in which several representations of a dataset can be personalized according to taste or convention, making it harder to relate individual data items in one representation to a specific data item in another. For example, relating one specific node in a Treemap to another node in a node-link diagram might require a search to locate the respective node in the other representation. Implementing mechanisms to highlight individual data items across representations might aid individuals when switching between group and more parallel data exploration.

Task History: Collaborative information visualization systems should also provide access to some form of data analysis history. While this is true for information visualizations in general [29], it might be of even higher importance in collaborative settings. Chua and Roth [3] have suggested that capturing and visualizing information about interactions of collaborators with objects in a workspace may enhance collaboration by leading to a better understanding of each others' involvement in solving a task. As group members switch between work on individual and shared views of the data, they might lose track of the interactions of their collaborators [8]. The access to an exploration history can help in later discussing the data and exploration results with collaborators or informing them about interesting data aspects that have been found during the analysis process.

Perception: Relatively little has been done to analyze how the interpretation of information visualizations is affected when viewed on different display configurations. A study by Yost and North [39] evaluated the scalability of three visualizations across a small and large, high-resolution display. Their study does not take the requirements of collaboration into account but provides several guidelines for designing visualizations for large displays: considering encodings according to viewing angle, choosing visualizations for scalable encoding, providing global and local legends, and strategic label placement. A study by Wigdor *et al.* [38] evaluated the effect of viewing angle on different graphical variables and suggests that care should be taken in positioning and choosing the appropriate visual encoding as some graphical elements are more robust to distortion than others. In the case of collaborative work around a large horizontal display, group members might

be positioned on different sides of the display, thus viewing shared visualizations from different directions. It has to be evaluated how the legibility of information visualizations is affected by different viewing directions. So far, it is not known if, for example, an upside-down bar chart would lead to inaccurate readings of the data.

3.3 Designing the Collaborative Environment

Pinelle *et al.* [21] provide a set of basic operations that should be supported by groupware systems to help collaborators carry out their tasks as a team. These mechanics of collaboration can be grouped into those describing communication and coordination aspects of collaboration. Collaborative information visualization systems also require additional support for communication, coordination, and changing collaboration styles to further the analytics process.

Coordination: In group settings, collaborators have to coordinate their actions with each other. Here, we describe several guidelines for how to support the coordination of activities in collaborative information visualization applications.

Workspace Organization: Typical single-user information visualization systems impose a fixed layout of windows and controls in the workspace. Previous research has shown that, on shared workspaces, collaborators tend to divide their work areas into personal, group, and storage territories [27]. This finding implies that a *group interaction and viewing space* is needed for collaborative data analysis where the group works on a shared representation of the data or in which shared tools and representations. Also, the possibility to explore the data separately from others, in a *personal space*, is necessary.

Fluid Interaction: Collaborative systems should support fluid transitions between activities to improve the coordination of activities [28]. This implies that information analysis tasks that require the application of tools (filters, lenses, etc.) or changing of view or visualization parameters should be designed to require (a) as little shift of input mode (mouse, keyboard, pen, finger, etc.) as possible, and (b) as little manipulation of interface widgets and dialogs as possible. For information visualizations, this is a difficult design problem, as systems frequently offer extensive lists of parameters to manipulate in order to provide flexible interaction. Similarly, the study on collaborative information visualization by Mark *et al.* [15] suggests that groups work more effectively if the interactions with a system are easier to understand.

Information Access: Information access through information visualizations also needs to be coordinated on a global and local scope. What if one group member found something in the data that he or she wishes to delete or modify? Who can change the scale, zoom, or rotation settings for a shared view of the data? Policies might have to be put in place to restrict certain members from making unsuspected global changes to the data that might change other group members' view of the same data [23].

Collaboration Styles: Tang *et al.* [32] describe how collaborators tend to frequently switch between different types of loosely and closely coupled work styles when working over a single, large, spatially-fixed information display (e. g., maps or network graphs). A study by Park *et al.* [20] in distributed CAVE environments discovered that, if the visualization system supports an individual work style, users preferred to work individually on at least parts of the problem. For information visualization systems, an individual work style can be supported by providing *access to several copies of one representation*. The availability of unlimited copies of one type of representation of data allows group members to work in parallel. More closely coupled or joint work on a single view of the data can be supported by implementing the possibility of *concurrent access and interaction* with the parameters of an information visualization. Free arrangements of representations also *supports changing work styles*. Representations can be fluidly dragged into personal work areas for individual or parallel work and into a group space for closer collaboration.

Communication: Communication is an important part of successful collaborations. People need to be able to trigger conversations,

communicate about intentions to change collaboration styles, indicate a need to share a visualization, and to be generally aware of their team members' actions. Providing awareness of global changes is important to support communication about the information analysis process [8, 3]. Group members need to be informed that some parameter of a shared display might have changed while they were busy working with an information visualization in a different part of the workspace. If group members decided to work in parallel on different subproblems, the visual comparison of the individual graphical exploration results has to be supported in order to make group discourse on the results possible. To enrich the discourse about individual visualization exploration results, additional interaction schemes such as annotation of the results should also be included [9].

Flexible workspace organization can offer the benefit of easy sharing, gathering, and passing of representations to other collaborators. By sharing data in the workspace, representations will be viewed by team members with possibly different skill sets and experiences and, therefore, subjected to different interpretations. Also, by being able to move and rotate representations in the workspace, an individual can gain a new view of the data and maybe discover previously overlooked aspects of the data display. Communication can also be supported through the design of gathering and sharing mechanisms. However, the design of these mechanisms needs to respect common social and work protocols [13, 23, 27]. For example, the interface should not require a group member to reach into or across another person's workspace in order to acquire or share visualizations or controls.

4 A SYSTEM FOR CO-LOCATED COLLABORATIVE WORK WITH INFORMATION VISUALIZATIONS

This section provides a detailed description of our information visualization system designed to support collaborative tree comparison tasks. Paralleling our design guidelines section we describe our hardware setup, our information visualizations and then those aspects specially included to support collaboration. Then, in Section 5, we describe this system in use for a collaborative tree comparison task.

4.1 Hardware and System Setup

Our system was designed to run on a large digital tabletop display; however, using it on large wall displays is also possible. Our digital table is built using a touch-sensitive DVIT Board from SMART Technologies with two concurrent and independent inputs (see Figure 1). The tabletop setup has $2,800 \times 2,100$ pixels (≈ 5.9 mega pixels) provided by four rear-mounted projectors (2×2). This setup offers an adequate size, configuration, input, and resolution for small groups of 2–4 individuals to work together. However, only two simultaneous touches are currently supported by our technology and inputs are not identifiable. Our implementation is based on a general framework for tabletop interfaces that provides a method of spatially representing properties of the interface using a buffer approach [10]. This framework and the buffer approach are able to maintain interactive response on high-resolution tabletop displays. We use the framework, for example, to implement picking and interaction regions for our widgets. The framework also provides access to other tabletop interaction metaphors and widgets such as RNT [13], tossing, and Storage Territories [26]. To facilitate not only an efficient management of memory resources but also to allow people to relate one visual representation of a dataset to a different one of the same data, we maintain only one copy of this underlying dataset. Each visual representation of a dataset is then realized using a set of meta data to represent the specific visual appearance.

4.2 Information Visualizations

Our system supports work with hierarchical data, specifically with two different types of tree representations: a space-filling radial tree layout and a cladogram. We have chosen to implement a radial tree layout as presented in [30], with a minor adjustment that places labels in a circular fashion inside the nodes (see Figure 2, left). We chose this type of labeling to facilitate orientation-independent reading from different positions around the tabletop display. Since tree comparison is a task commonly performed on phylogenetic trees [18] we also implemented

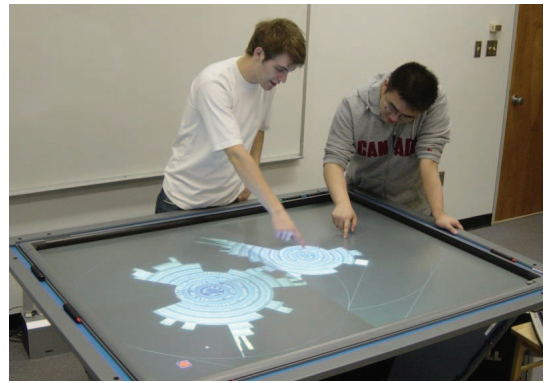


Fig. 1. The hardware setup for our collaborative information visualization application. Two simultaneous pen or finger inputs are possible.

a cladogram tree layout (see Figure 2, right). In the cladogram layout, all leaf nodes are extended to the bottom of the graph. To additionally reveal their place in the hierarchy, nodes are coloured according to their level. Our system can easily be extended to support other types of representations.

Any information visualization and all control widgets in our system can be freely re-oriented and repositioned. Each information visualization is drawn on its own plane with appropriate controls attached to the side. The left of Figure 3 shows a single visualization plane showing a radial tree layout and its attached menu buttons. The menu offers common view parameter changes: scaling (zoom), integrated rotation and translation [13], translation only, and annotation. Thus, the plane and attached visualization can be freely moved around the tabletop display. The right of Figure 3 shows an arrangement of three visualization planes on the tabletop display.

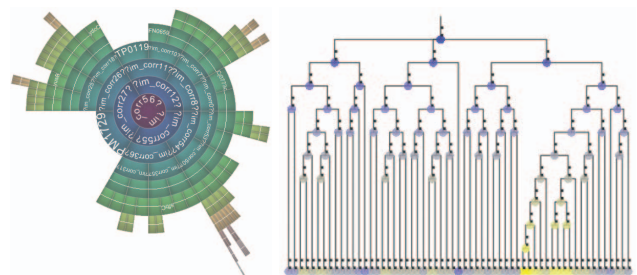


Fig. 2. The two representations used in our system. *Left*: a radial tree layout with radial labeling. *Right*: a cladogram with additional node colouring to reveal level information.



Fig. 3. A single *visualization plane* showing a radial tree layout can be seen on the left. The right image shows three visualization planes oriented on the tabletop display.

4.2.1 Supporting Mental Models

In Section 3, we have identified the creation and maintenance of mental models of the data set as one of the possible benefits of allowing users, rather than the interface designer, to impose a layout of visualizations in the workspace. By supporting free rotation, translation, and scale, users of our system can create their own organization of items by putting them in piles creating a preferred layout (e. g., small multiples). The possibility for organizing representations of data is further supported by providing storage containers that hold visualization planes. In these containers, visualizations can be grouped together, resized, and moved as a unit (as in [26]). Figure 4 shows an example of a visualization plane being placed in a storage container. First, the plane is dropped on the container (left), and then automatically resized and placed in the storage container (right). Items in the storage container can be placed casually, neatly organized, or piled, and can then be moved as a unit. These containers can provide a means for collaborators to store intermediate exploration results for later reference or comparison.

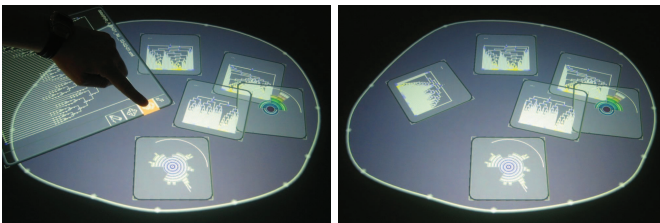


Fig. 4. A visualization plane is being dropped on a storage container (left) and automatically resized and placed (right).

4.2.2 Representation Changes

To support changing decision-making strategies and personal tastes and conventions, we provide individual access to different types of representations. If an individual group member wishes to visualize the data using a different but appropriate representation of the data, e. g., a containment tree layout instead of a node-link diagram, the specific representation can be changed with a drag-and-drop operation without interfering with other group members' operations. Figure 5 shows how a representation change is performed. In the left image the visualization plane is dragged onto the RepresentationChanger widget. As soon as the plane has been placed on the widget, the representation changes to the desired one as can be seen at the right of Figure 5.

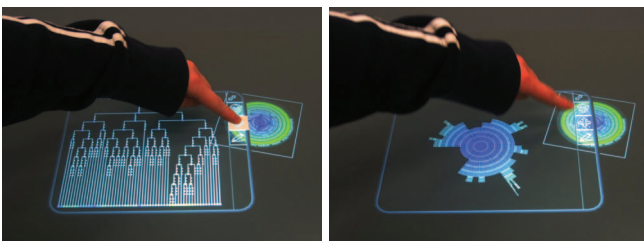


Fig. 5. Switching a representation type with a drag-and-drop operation.

4.2.3 Task History and Perception

Our system currently only includes annotation and note taking capabilities to capture exploration history (see Section 4.3.3). Further capabilities will be designed and evaluated for future versions of our system. As few evaluations (e. g. [39, 38]) have discussed the effects of perspective distortion and orientation on the readability of information visualizations we have not attempted to correct for possible negative effects.

4.3 Design for Collaboration

In this section we discuss the features of our system according to guidelines for the design of the collaborative environment as presented in Section 3. At this time we have addressed issues concerning workspace organization, fluid interaction, supporting differing collaboration styles, and communication.

4.3.1 Workspace Organization and Collaboration Styles

Free workspace organization allows us to support different work styles. Collaborators can fluidly transition between more independent work and closer, joint work on information visualizations. Figure 6 gives an example in which two collaborators are working individually at first, looking at visualizations in their own area of the workspace (Figure 6, left) and then switch to a more closely coupled work style by investigating one visualization together in more detail (Figure 6, right). Note that the scaling mechanism has been applied to create a larger visualization to accommodate the concurrent interaction and viewing of both partners and that the plane has been rotated towards both team members. This type of rotation has been previously identified as a strong communicative gesture [13].



Fig. 6. Visualization planes can be freely arranged in our system. On the left two collaborators are looking at a few representations individually. On the right they are investigating one visualization together.

Any number of windows can be created, moved, and interacted with in the workspace, limited only by the complexity of the graphics and the capabilities of the graphics hardware. By allowing collaborators to each access a copy of a representation we support parallel work on the same data. Each dataset loaded into our system is represented as a floating menu entry in the workspace, as can be seen at the left of Figure 7. The menu entries can be freely repositioned and, thus, passed to other collaborators to facilitate shared access to this resource. A new visualization plane with a representation of the data is created by pointing on the menu entry (see Figure 7, right). While initial response has been enthusiastic, we realize that many careful studies are required to evaluate the varying effects of our tools on group work.

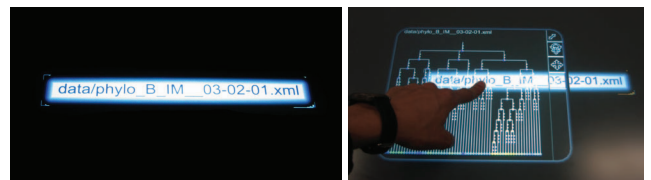


Fig. 7. Creation of additional representations using floating menu entries. *Left*: an example of a floating menu entry on the tabletop display. *Right*: A user created a new visualization by touching the menu entry.

4.3.2 Fluid Interaction

Our hardware supports input using fingers or pens and reports touch information (touch down, touch up) to the interface application. We, therefore, have to design interaction techniques without common interactions known from the desktop, like double, left, or right click. In desktop software, dialog boxes or spatially fixed menus or parameter panels are usually used to change visualization parameters for a

given focus view. Most traditional widgets are not suitable for providing fluid interaction (see Section 3) and to be concurrently accessible by several group members. During parallel work in a group setting, several visualizations might have a focus at the same time or a visualization might be interacted upon by more than one person at a time. Research on a system for collective co-located annotation of digital photos [22] revealed that users strongly preferred a replicated set of controls over a centralized shared set of controls because the center of the table was needed for other tasks and because replicated controls avoided accidental touching by other teammates. We, therefore, decided to use a replicated set of controls where each control could also be freely positioned.

Currently, our implementation supports the change of visualization parameters as drag and drop operations. For example, we implemented ColourChanger widgets on which a visualization can be dropped in order to initiate a change of its colour scale (see Figure 8). Alternatively, these widgets could also be dropped on the visualization plane in order to reposition visualization planes if a careful layout has been created by the group. We are also experimenting with other input techniques like flow menus [7] in order to make a large number of parameters accessible for each visualization plane.

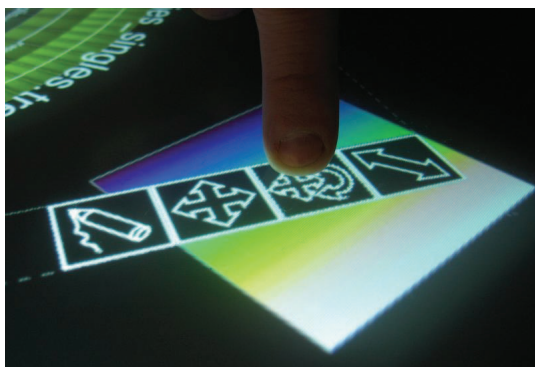


Fig. 8. A visualization plane is dropped on a ColourChanger widget that changes the colour scale with which the tree is displayed.

4.3.3 Communication

To enrich the discourse of individual and group exploration of data our system allows for annotation directly on the provided visualizations and separately on sticky notes. Interactive sticky notes for low-resolution input [11] can be used to take general notes during the exploration process to, for example, write down intermediate results or variables to look for. Using these annotations, collaborators can become aware of each others' exploration processes even if the individual work takes place in separate areas of the workspace. Figure 9 shows how sticky notes and integrated annotations can be used to mark interesting information in a tree layout. By allowing visualizations to be freely repositioned we offer a mechanism for *sharing of visualizations* as the windows can be easily passed to the other collaborators. Representations can also be passed by dragging or tossing them across the table, similar as implemented for pictures in [26].

5 COLLABORATIVE TREE COMPARISON

In this section we show how our system functions by stepping through a task of collaborative tree comparison. We use an example based on the InfoVis 2003 contest³ dataset, showing how our system supports collaborative comparison tasks.

5.1 Data and Task

As example data for our comparison tasks we used the InfoVis 2003 phylogenetic data and tasks. This dataset contains information on the

³<http://www.cs.umd.edu/hcil/iv03contest/>

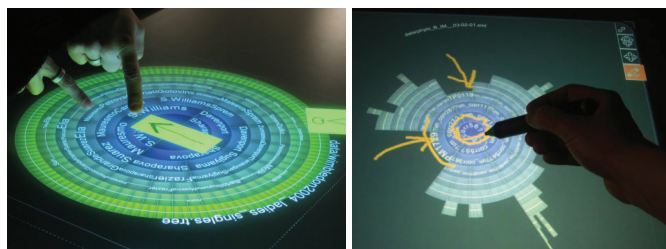


Fig. 9. Annotation of visualizations. *Left*: Annotation using interactive sticky notes [11]. *Right*: Annotation integrated directly on the information visualization.

evolution of two proteins (Protein ABC and Protein IM). It has been suggested that both proteins co-evolve and that such a co-evolution can be detected by comparing the phylogenies of both proteins. The high-level task was to find out whether such a co-evolution was visible. Lower-level comparison tasks included finding where structural changes occurred in the tree. We chose to use the two main files for the ABC and IM proteins and the additional four trees that were provided. We did not pair proteins between the two trees.

5.2 Tree Comparison Algorithm and Visualization

We used the same similarity measure as used for the TreeJuxtaposer system [18], which is based on comparing the sets of labels of nodes in the subtree under each node. The best corresponding node(s) and nodes with no similarity were highlighted. Figure 10 shows a comparison of two trees containing different versions of a carnivore hierarchy. The node “dog” has been selected by a user in the left tree. The best corresponding node “dog” in the right tree is highlighted in yellow, whereas nodes with no similarity are highlighted in red. Nodes in blue are not highlighted in the right tree as they contain the node “dog” (yellow) in their subtree and are therefore “somewhat similar.”

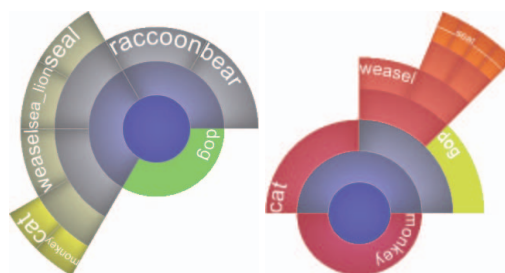


Fig. 10. Tree Comparison of two different versions of a carnivore data set. *Left*: The node “dog” has been selected for comparison. *Right*: The node “dog” is highlighted in yellow as the best corresponding node. Nodes in red have no correspondence with the node “dog.”

Trees in our system can be compared by moving their visualization planes close to one another. When planes are close enough for comparison, the borders are highlighted and nodes can be selected to start a similarity calculation. In Figure 11, we show two planes on the left in comparison mode (orange border) and a smaller tree to the side that is not currently compared. Any number of trees can be compared by moving them close to others that are already being compared.

5.3 Solving Collaborative Tree Comparison Tasks

To gain an overview of the available information, each visualization plane can be arranged to facilitate a comparison between all available datasets. In Figure 12, two users of our system created a comparison overview by organizing their planes to facilitate cross-comparison. Figure 13 shows a close-up screenshot of such a comparison. The middle two planes show the main IM and ABC protein representation. The root node of the ABC protein (top row) has been highlighted (green). The two trees on the left, the alternative versions of the IM protein,

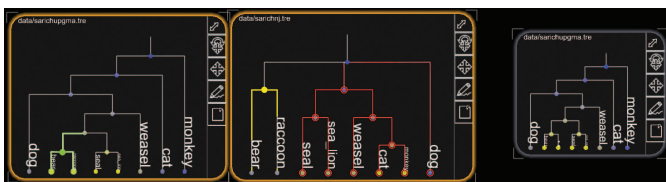


Fig. 11. Trees can be compared when their planes are in close proximity. Here the two planes on the left are in comparison mode as can be seen by the highlighted (orange) border. The tree on the right is not currently compared with the others.

and the IM protein tree show only dissimilar nodes to the ABC protein (in red). However, the alternative versions of the ABC proteins both show a few dissimilar nodes that need to be inspected further.



Fig. 12. All six datasets have been moved together to facilitate a comparison across all representations.

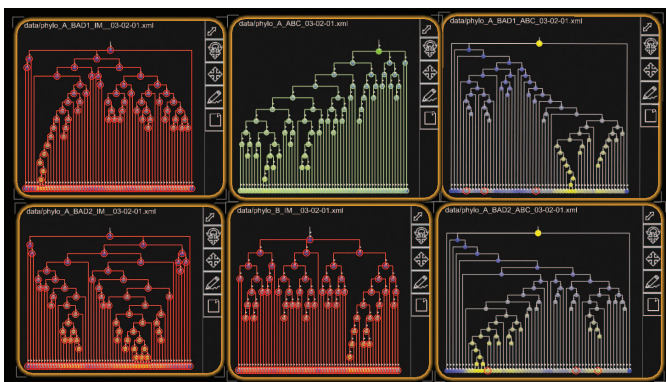


Fig. 13. Screenshot of the system showing all six trees. The root node of the ABC protein in the top center plane has been highlighted.

This more detailed investigation within the versions of the ABC and IM protein was performed in parallel. The left of Figure 14 shows two collaborators who have decided to each investigate one of the proteins. To inspect which nodes have dissimilar values, they have chosen to annotate the dissimilar nodes first and to then examine the nodes and their structure in the hierarchy in more detail. However, closer examination of nodes can also be performed in joint work as shown in Figure 14 (right).

A contest task required the examination of the hierarchical structure in terms of whether subtrees moved in the hierarchies or nodes changed position. To facilitate a structural comparison of nodes in this sense, trees in our system can be overlaid and then examined. All visualization planes are semi-transparent in order to support this type of tree comparison. Figure 15 gives two examples of structural comparison through overlay. The top image shows an overlay of Protein ABC (blue) and Protein IM (magenta). It can be seen that Protein ABC is generally more shallow than Protein IM but has one main subtree that is wider and deeper than can be found in the other tree. In the bottom



Fig. 14. Closer examination of a few trees. *Left*: Parallel work with each person comparing three trees each. *Right*: Joint work comparing four trees together.

image, two users overlaid their exploration history including annotations of similar trees. Similar and dissimilar nodes are highlighted. We are considering options to auto-rotate planes to show the best possible match.

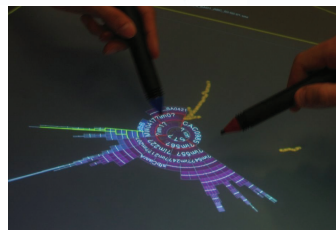
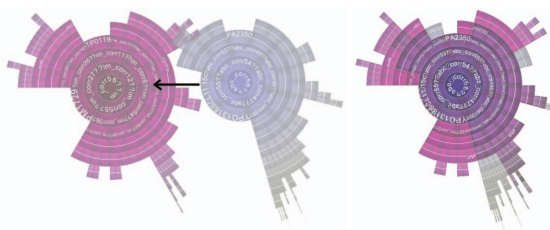


Fig. 15. Structural comparison through overlay.

6 CONCLUSION

In this paper we have provided guidelines for the design of co-located collaborative information visualization systems. We have applied these guidelines in the creation of a system for collaborative tree comparison tasks and have shown how such tasks can be solved in a collaborative fashion using our system. So far, most information visualization systems have been designed with a single user in mind. How—or whether—interfaces, visualizations, and interaction techniques should be designed to specifically address the needs and requirements for teams of individuals analyzing data still needs to be further explored. In this paper we have contributed to the evolving knowledge about the design of such systems. Our guidelines have been derived from general information visualization design advice, co-located collaboration advice, the few studies that look directly at collaborative visualization, and our observations of teams of people working together to solve tasks using information visualizations. As our collaborative system is evaluated and developed further, and as other researchers contribute to the development of collaborative information visualization systems, we expect these guidelines to be extended.

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