State of the Art: Coordinated & Multiple Views in Exploratory Visualization

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Abstract

The area of Coordinated and Multiple Views has been steadily developing and maturing over the past fifteen years. Some may say that it is a 'solved problem', while others argue that we are only just scratching the surface of the subject. Considering merely the CMV conference series, it is clear to see that in the early years researchers were concerned with models and techniques, while in latter years authors presented more work on how to apply these ideas to different domains. It is our view that there is still much research to be done, but the subject is changing and developing as a tool for Visual Analytics. This paper provides the 'state of the art' of CMV, it describes areas that should be developed further and looks at what the future may hold for Coordinated and Multiple Views.

Keywords— **Coordinated and Multiple Views, Linked Views, Information Visualization, Exploratory Visualization**

1 Introduction

Multiple Coordinated Views is a specific exploratory visualization technique that enables users to explore their data. In fact, the overall premise for the technique is that users understand their data better if they interact with the presented information and view it through different representations.

On the one hand, users want to look at complex and intricate data; they want to explore and find out some facts that are not easy to find. These complex investigations require the user to consider many scenarios, to compare visualizations generated from multiple different datasets, to aggregate and mine the data, perhaps fuse data from multiple diverse datasets to generate new information, and be able to easily roll back to a previous incarnation. Furthermore, different experts may be looking at the same data and may wish to compare and discuss exploration paths and conclusions. These complex analytic investigations hence require the exploratory tool to have comprehensive yet intuitive functions.

On the other hand, users may be too familiar with the techniques they use and consequently may be missing out on the richness of the underlying data. Therefore, by utilizing a visualization design environment that enables the user to examine different representations and also manages their interactions and automatically coordinates operations between views, then they may perceive new and insightful relationships and facts from their data.

Figures 1,2,3,4 show screen shots of some CMV systems that have been recently described in the literature. They all allow the user to see the data in various forms, to manipulate the visual presentation in different ways, and also interact and coordinate the interaction between the different views. The examples also demonstrate that these techniques are applicable to a variety of domains.

Principally the concept is to allow the user to have a dialogue with the data. The goal is to find information and make sense of the large volume of potentially diverse datasets of multiple components and types. The user wishes to understand trends, locate anomalies, isolate and re-organize information, compare and make clear any differences or similarities between datasets [21, 71]. Furthermore, the user is able to examine scenarios and develop hypothesis through a systematic search. In order to achieve this the developer needs to make a highly interactive visualization environment that enables the user to find and discover new understanding. These interactive systems have at their heart the Coordinated and Multiple Views technique. The user interacts with the data to both formulate a problem and concurrently solve it [65]. Insight is thus formed through the interaction of the data.

The conference on Coordinated and Multiple Views in Exploratory visualization is now in its fifth year. The existence of such a specialist conference demonstrates the importance of this area. In fact, the growing subject of Visual Analytics has as its core functionality the technique of CMV. Hence, it is important to analyze the state of the art in CMV. This paper looks at where we are with Coordinated and Multiple Views (CMV) for Exploratory Visualization (EV), it discusses areas where we are and are not succeeding and looks toward the future. The concepts in this paper have been refined from opinions and discussions

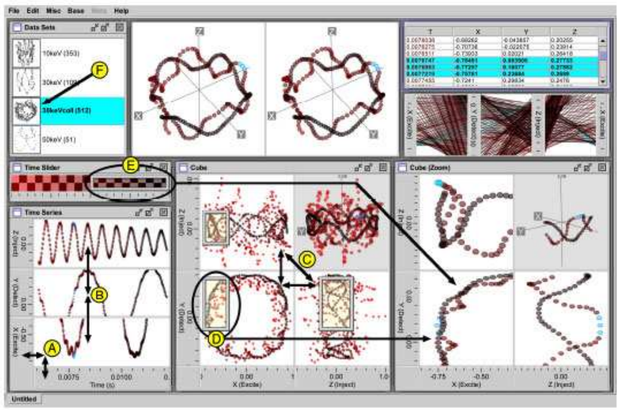

Figure 1: **Improvise** [77]. The visualization depicts data from a simulated ion trajectory in a cubic ion trap. The multiple different views are coordinated to control various aspects of the exploration. (A) and (B) control the time series, (C) is a scatterplot matrix showing the trajectory, (D) represents a selected subset (E) represents a slider to select a range of values. (F) shows a 3d thumbnail of each trajectory. Used with permission.

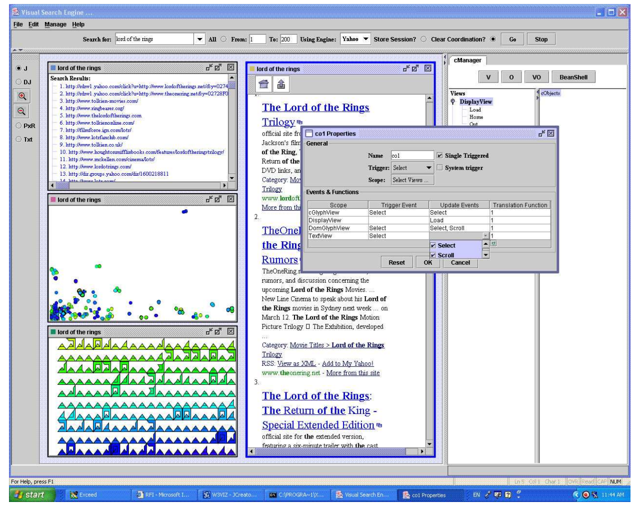

Figure 2: **The Visual Search Engine** [10]. The picture shows four views and the control panels to determine how and what information is coordinated. User defined functions can be added, through a bean shell, to determine any mapping. Various operations can be performed such as zoom to selected elements while brushing them in another window, or highlighting the inverse of those selected in another linked view.

held at CMV Conferences. Hence, we are indebted to these comments and suggestions. This paper is not meant to be a comprehensive review of the area and so does not include a complete list of references. The references support the arguments and the discussion points made in this article.

Following closely to the knowledge crystallization model [14, 46], this paper covers seven fundamental areas of CMV:

- Data Processing and Preparation, section 2
- View Generation & and Multiple Views, section 3
- Exploration techniques, section 4
- Coordination & Control, section 4.2
- Tools & Infrastructure, section 5
- Human interface, section 6
- Usability and Perception, section 7

2 Data Processing and Preparation

Consider the knowledge crystallization model. In order for a user to visually explore the data, the data first needs to be processed and prepared. Although, data preparation is not solely a CMV issue data processing can have particular implications for the EV user. It is perhaps incredible, that after years of developing visualization solutions that the data preparation phase still takes a long time [71]. If the dataset is large it may need to be aggregated or mined to simplify it. Data often needs to be *cleaned* to remove erroneous values, and different diverse datasets may need to be fused together to provide the knowledge required.

In fact, one of the main challenges to exploratory visualization comes from the huge quantity of data. Large datasets contain more complex relationships, take longer to process and are thus slower and more confusing to explore. If the user is generating a lot of views then they do not wish to wait while one view finishes rendering before continuing. Hence, naïve linear search algorithms used in coordination, that work satisfactorily on small datasets, need to be exchanged for better algorithms. Or techniques to incrementally visualize the results while the high detail view is rendering, need to be used. Furthermore, techniques such as using parallel algorithms [30] or grid based architectures [3, 12] can also help, but in reality few researchers have included these techniques with CMV systems. Data mining techniques can also help, generating categorizations and summary information and reducing the quantity of data to be presented. Indeed, researchers have called for a closer link between exploratory visualization and data mining techniques [35, 36].

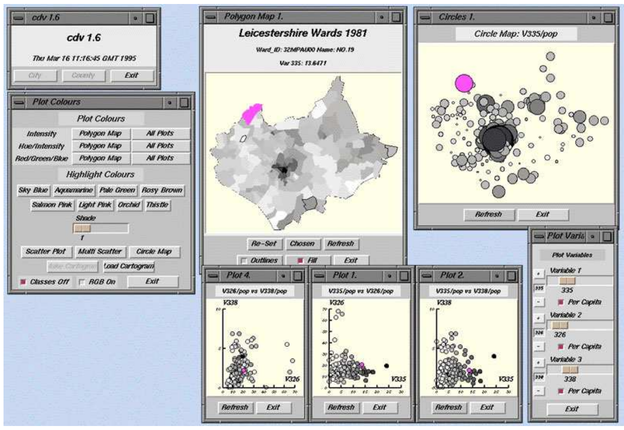

Figure 3: **cdv** [22]. Demonstration of cdv showing various geographical and statistical views that are linked together. Used with permission.

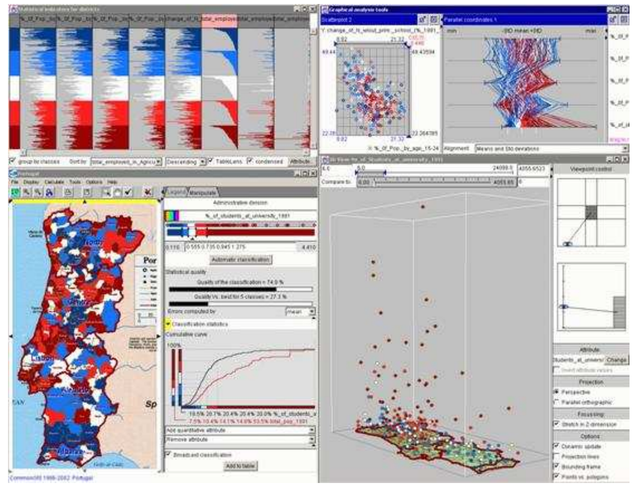

Figure 4: **CommonGIS** [5]. The visualization depicts multiple linked views with the space-time cube visualization. Used with permission.

Processing and exploring temporal data is also a challenge for CMV systems; if time is represented through animation (such as by Craig et al. [19]) then it can be difficult to navigate; while if time is represented by space (such as in temporal view lines [2], or the 2d events plot by Morrison et al. [41] or through the dense pixel views of Shimabukuro et al. [62]) then the display can take up a large area of the screen.

Datasets often include missing or erroneous information. Techniques to visualize this inaccurate have been around for a while [33], and have been integrated with some systems (such as Manet [73]) but few developers incorporate techniques to handle or visualize this information in their CMV systems. Most systems require the missing information to be 'removed' by substituting an average value. But, missing or erroneous information on its own or fused with information from another database can help the user in their understanding of the information [71]. In fact, data fusion techniques are still in their infancy and have not been fully integrated with CMV systems.

2.1 Summary: "Data Processing and Preparation"

There are certainly many data processing techniques, and these support the user in their exploration process. Many techniques have been developed and researched to provide parallel computation and parallel algorithms to increase the running speed of the algorithms, there has also been much research into controlling missing or uncertain information.

But, data preparation and processing are still challenges faced by developers and users today. For instance Yang et al. [79] write that the user needs to wait until the operation has finished before achieving another operation. In fact the problem is increasing, not only because of the size of the datasets but that users are wishing to incorporate and fuse the data from multiple datasets. Users rightly want highly interactive systems that are both easy to use yet functionally rich. Although, much work has been achieved to speed up and make the processing more interactive more work needs to be done if we are to keep up with the demands from the user. Likewise, for both uncertainty visualization and data mining techniques developers have created various solutions but again these have not been tightly integrated with CMV systems. Finally, processing temporal data is still a challenge for CMV systems.

3 View generation & Multiple Views

The developer has to make several decisions when generating visualizations. First they need to decide what form the visualization will take and then work out how that information will mapped to that form. Concurrently they need to decide how the information will be aggregated or abstracted and finally work out how the user interacts with the system.

After deciding on the style of visualization one of the main choices, for a CMV developer is to decide what gets updated when parameters are changed. Roberts described a model of three parts: *replace*, *replicate* and *overlay* [51]. Replacement occurs when on a parameter change the new information replaces the old. Replication occurs if the new information is displayed in a new window. Finally, an overlay is made when the information is merged with the old. Obviously replication is the principle model of CMV, however the user needs to exercise caution regarding how much they use each category. When replacement is used, often the history of past operations is also lost and thus extra support is required to manage the user's history. When using replication it is far too easy for the user to get swamped in a mass of views. Whereas, when the information is overlaid or layered in the view then the display may become incomprehensible.

Making interactive systems that are usable is a difficult challenge for any developer. Indeed, there are many different styles of user interface to create the desired multiple view functionality. These typically fall into one of three categories. First, the functionality may be controlled through menus and buttons, such as CommonGIS [5], cdv [22], Snap [42] and Mondrien [70]. Some systems provide dynamic queries where users can interactively explore and change parameters of representation, while other systems allow the user to create views through menus and some form of visual programming (e.g. Improvise [77] and Ross and Chalmer's visual workspace [55]). Second, are the systems that follow a modular approach. Such Module Visualization Environments (MVE's) often follow the dataflow paradigm and have predefined set of modules that can be linked together to form the visual program, which provides a convenient and extensible way to build the visualization solution [56, 74, 75]. Users can easily create multiple views but coordination between these views can only be achieved through a convoluted set of commands and additional modules. Third, some systems create the representations through automatic algorithms from (say) user preferences [58]. Obviously as the user is wishing to evaluate ever complex datasets the demand for systems that simplify the operations by automation is growing. Techniques that aid, persuade or automatically suggest additional visualizations can help the user in their exploration, but they can also hinder the user in their task. In fact, historically such suggestion systems have not always been welcomed. Thus, it is perhaps better to give the user some choices [52]. Although some work has been done in this area much more work needs to be done to integrate these techniques into CMV exploratory systems.

3.1 Visualization forms

It is encouraging and not surprising that developers and researchers have created many visual forms. Thus, the developer certainly has a wide variety of visualization styles to choose from. Based the classification of Lohse et al. [39] researchers have developed: *maps* including choropleths [23] and other forms of spatial representations; *networks* and other associated data, e.g. Rodgers provides an overview of graph drawing techniques for geovisualization [54]; *charts and graphs* including scatter plots, bar charts, line graphs, parallel coordinate plots form the principle components of most CMV systems such as cdv [22], Mondrien [70], CommonGIS [5]; *tabular and matrix layouts* have also been used in CMV systems, such as the reorderable matrix [64], table lens [49] and spreadsheets [31]. Finally, symbols and glyphs displays have been used successfully in CMV systems [5, 22].

3.2 Multiple Views

Various names have been given to different aspects of *multiple views* and different authors have used the terms differently. In this section we present the breadth of the types of multiple views that are available and provide our interpretation of these terms.

The term *multiple views* is the general name used to describe any instance where data is represented in multiple windows. It usually implies that different representations are placed in subsequent windows and that operations on the views are coordinated, hence the longer term *multiple coordinated views* may be used. On the other hand, the words *form* and *multiform* are specific. A form is a type of visualization (such as a parallel coordinate plot or scatter plot) while multiform is used to described that the data is displayed in two or more different forms. The term *alternate representations* describes the situation where there may be multiple interpretations of the data, and hence different viewpoints from those interpretations [53]. This is obviously useful in education as the learner may understand the information better through one presentation rather than another.

Through multiple views and multiform representations the user can easily compare the data from two or more representations. Specifically, systems that solely use two *side-by-side* views are named *dual view* systems [18]. There are a few dual view variants. (1) *Overview+detail* shows the whole dataset in one view and the other view as some detail. To generate the overview the information needs to be abstracted, simplified and aggregated in some way. Especially with large datasets it is often difficult to generate a good overview without biasing the representation. (2) *Focus+Context* is another methodology to give detail in one area and show the context of that information in another (although, many focus+context techniques utilize distortion to show the context and detail in the same view). (3) *Difference views* merge two or more views together to explicitly show the difference, they have been used to evaluate algorithms or used to highlight textual differences [61, 68]. (4) *Master/slave* relationships are also dual views where one representation controls the other. (5) In virtual reality it is possible to use "World in Miniature" or 'view on a bat' techniques to control aspects of the main view [66] (6) Finally, although not strictly dual-views, small-multiples [72] are a matrix of small visualizations that are laid side-by-side, often these are glyphs or symbols created from the data.

3.3 Summary: "View generation & Multiple Views"

There are certainly many different styles of visual forms and each have their benefits and drawbacks. Over the last ten years researchers have without doubt refined the ways in which data is visualized and displayed, and so today the developer and user have many creative methods to their disposal.

However, with this choice comes a challenge; which method is effective and when should it be used in place of is another? Recently there has been some work done evaluating which method is suitable, and how users best perceive information from multiple view environments [18, 63] but more work is required in this area. Furthermore, certainly the development and use of intelligent or persuader systems seem promising, but should be closely integrated better with CMV systems. Some work has been achieved in the area of comparison and difference visualization, but this work is not integrated well with CMV systems, in particularly the use of *difference views* is extremely useful but hard to achieve in practice. Finally, to create the dual views, often the information is summarized, aggregated or abstracted to generate the overview. Some work has been achieved to integrate the control of aggregations into CMV systems but more work on aggregations is required.

4 Exploration Techniques

Multiple Coordinated Views is a particular solution to exploratory visualization, and the user can interact with the data in various ways. Theoretically any operation can be coordinated between multiple views [10]. As we have seen generating and specifying the content of the view is one part of exploration, and that was covered above (section 3). In this section we cover manipulation and coordination.

4.1 Interaction & Manipulation

CMV systems integrate a large variety of different interaction strategies. In fact, the user can interact with the system to change the data processing, to filter the data and select what is displayed [6], change how the information is mapped (such as by changing the colourmap), navigate the information (zoom in and out and fly round the data [47]) and change where the windows are placed on the screen (such as the dynamic splitters in the GeoWizard GUI [26]). There are two styles of interaction: indirect and direct manipulation.

Indirect manipulation includes *dynamic queries* [60] where the user interacts with sliders, menus and buttons to filter the data and change how the information is displayed. The sliders represent both a way to interact and determine what is visualized and what constraints are placed on what data is viewed, but also provides a visual representation of those values. In fact, often the range sliders are integrated directly with a parallel coordinate plot. For instance, range sliders have been used by Shimabukuro et al. [62] and these techniques have been incorporated in many CMV systems (e.g. [6, 11]).

Direct manipulation techniques allow the user to filter or select elements from the visualization itself. The technique of *brushing* is the principle approach, where elements are selected (and highlighted) in one display, concurrently the same information in any other linked display is also highlighted. Much of the original work was done on scatter plot matrices (Carr et al. [15] and Becker and Cleveland [8]). All modern CMV systems provide some brushing capability. With brushing the user can change the style of the brush (e.g. Piringer et al. [45] and Weaver [78] use a bounding region brush), or the area that the brush effects, or what happens to the elements when they are selected (e.g. often the color of the selected elements is changed [56]). Brushing is often good to discover outliers between multiform views [37]. Other direct manipulation techniques utilize *manipulators* and *widgets* directly attached to objects to change their properties. For example, Chuah et al. [17] provide handles to control parameters directly. Similar handles have been placed on parallel coordinate plots to directly control and threshold values [6, 11, 24].

4.2 CMV and the exploration process

As the user explores their data so they generate and compare the results placed in these multiple views. There is certainly structure in this exploration and various researchers have presented various theories explaining this structure. First, on a parameter change the next view is obviously related to the first. Hence, the views can be grouped together, these are often called *render groups* [50]. Second, because the user can interact with the data in different ways there are obviously various reasons for coordination. Common reasons include data preparation (sorting, averaging and clustering [43]), *selection* and *navigation* [42] also called navigational slaving. In fact, any aspects of the visualization process (from data processing, through mapping and rendering, navigation and manipulation to window manipulation) could be coordinated, as detailed in the layered model by Boukhelifa et al. [10]. Third, as the user explores so the coordination requirements over the exploration session may need to change. Cruz and Huang use previous settings to link views together [20], while Boukhelifa et al. [10] present 'rudiments of coordination', they detail that the coordination 'event' has *type*, *scope*, *lifetime*, *initializer* and *update* requirements.

4.3 Summary: "Exploration Techniques"

There is certainly a wide range of exploration techniques that can be included with any CMV system, from indirect manipulation techniques that utilize sliders and menu operations to constrain the viewed results, to direct manipulation techniques that allow the user to directly manipulate with the visualization display.

However, many tools do not implement the full set of functionality that is available, for instance, developers seem to forget the rich aspects of brushing. Elements can be removed as well as added from the brushed list, brush operations can be compound [16] or determined by some underlying structure [29].

5 Tools & Infrastructure

This section briefly evaluates where we are with developing models, systems and toolkits to help users build effective CMV systems.

5.1 Coordination Models/Architectures

Many researchers have presented theories and models for exploratory visualization, and it is impossible to do this justice in such a small part of a conference paper, however we detail the main models that are directly related to CMV.

There are three principle architectures to achieve view coordination. First, the constraint approach, such as the constraint system based on the presentation graphics programming model by McDonald et al. [40]. Second the data centric approach that draws its inspiration from the database community, where relational database components are tightly coupled such that an interaction with one component results in changes to other components (e.g. Snap [42]). Third, the Model View Controller approach. Pattison and Phillips [43] use a MVC approach where the presentation component observes the model for changes and updates its display as necessary. The model component observes both the specification and data model components for change and alterations to the specification component are propagated up. Likewise, Boukhelifa et al. [10] detail an Abstract Model for coordination as their underlying coordination strategy. Where the coordination objects notify the view of any changes. The values taken from the notification can be subject to an arbitrary function.

5.2 Tools & Toolkits

There are many systems that demonstrate coordination across multiple views, far too many to cite in this paper. However, some of the systems are classical examples of particular coordination forms. For instance, Felger and Schröder [27] in the visualization input pipeline (VIP) describe linked cursors, another example of linked navigation is by Plumlee and Ware [47]. Other forms of navigation include data probing, as implemented within both LinkWinds [32] and KBVision [4] and changing the viewport information, as accomplished in SciAn [44] and Visage [57] which provide coordinated manipulation of 3D views. Linked brushing is implemented in multiple systems including DEVise [38], XmdvTool [76] and Spotfire [1].

Some developers create specific systems that address a particular need, while others develop more general systems that can be applied to a wide range of problems and can be adapted by the user. Tools like Tioga [67], LinkWinds [32], DEVise [38], CommonGIS [5], Snap-Together [42] GeoVISTA studio [69] and Improvise [77] all allow the user to define and browse highly-coordinated visualizations.

There are many different libraries and toolkits that can be used to create the CMV system. Languages such as Java provide a convenient medium for development [10] and libraries such as the InfoVis toolkit have been designed to aid Java developers to provide "specific data structures to achieve a fast action/feedback loop required by dynamic queries" [25]. But, developing CMV tools is still challenging. Lately there has been interest in utilizing beans and component technologies. For instance ILOG's Jviews[1] components for Java and GeoWizard uses Microsoft's .NET technology that allows multiple environments to be "built without the need for programming" [26].

5.3 Summary: "Tools & Infrastructure"

Many CMV demonstration systems have been presented and various systems allow users to develop highly interactive coordinated multiple view systems.

But, it is still difficult and lengthy to develop these highly coordinated systems. Component technologies is one solution that seems promising. However, underpinning technologies such as data structures and parallel algorithms seem to be an after thought. Fekete [25] in his InfoVis toolkit does provide techniques to specifically address challenges from data structures and underpinning technologies. Moreover, GRID or web service technologies are developing rapidly that could impact on CMV system development. In fact, developers are starting to consider further aspects of interoperability and extensibility. Systems should be interoperable and there are challenges to allow them to work together, and make them fully extensible.

[1] www.ilog.com/products/jviews/

6 Human interface

CMV systems by design present the user with many windows, parameter choices and much information. There is therefore a range of techniques that can be implemented to enable the user to understand the interface and perform their tasks better.

6.1 Session Management

Managing the user in their exploration session is important. It is very easy to generate many views and forget how each view related to the exploration. The first aspect to manage involves the user's history session. Some tools provide a canvas [50] or utilize dataflow modules [56] to *manage the session*, but few tools include the rich functionality required to effectively manage the session history. Techniques such as saving the session history and allowing different users to edit and adapt the history in order to confirm and extend exploration paths are missing. Also techniques to control the session history with multiple participants over different time zones have not been researched thoroughly. Research has started to look at the challenge of managing the user in this exploration (such as vistrails [13]) and provenance for visual exploration systems [28], but further research is required.

Due to the limited screen size that is typically available to a user another important challenge is to aid users in their *window management*. Systems can either leave this up to the operating system or provide specific functionality to aid the user in this task. Strategies include iconization [50], deletion of unwanted windows and constraining how the windows are placed on the screen (such as the dynamic splitters in the GeoWizard GUI [26]). Other window management strategies exist in the literature such as zoomable user interfaces (ZUI's) [9] and elastic windows [34] but these techniques have not been integrated into CMV systems.

6.2 Meta-information

Meta-information is subsidiary information that can aid the user in their task. There are two styles of meta-information. The first comprises details about the state of the system or helpful hints of how to use the system, whilst the second holds additional information about the data.

As it is sometimes difficult to understand which view relates to what information and how the system is setup (e.g. which views are coordinated together). It would be useful to visualize this information. For example, Improvise [77] explicitly visualize the conceptual interactive structure of the system. One example demonstrates what views are linked together through arrows that are annotated on top of the visualizations.

There may be additional information that is not traditionally visualized that may influence the user's decision. Aspects that could be visualized include the resolution of the sensor, when the original data was collected, who created the data, what are the error rates etc. Currently CMV systems do not fully integrate this type of meta-visualization.

6.3 Display medium

When a user is exploring their information they may wish to have a huge screen to see all the information without overlapping views. Using ZUI's [9] is obviously one solution, another is to use large projected screens or tiled displays. Sandstrom et al. [59] described a system to integrate LCD panels into a 7x7 array screen to visualize and coordinate multiple visualizations, while companies such as 9X Media[2] offer technologies that utilize multiple abutting LCD panels to realize one large screen. But, along with the increase of larger displays users are also wishing to coordinate smaller hand-held devices together with the larger visualizations. Techniques to utilize very large or very small screens with CMV systems have not been fully researched.

6.4 Summary: "Human interface"

Researchers have developed some useful window management strategies (such as dynamic splitters [26], ZUI's [9] and elastic windows [34]), but many of these techniques are not fully integrated with CMV systems. Furthermore it is still hard to manage the EV session: exploration control is still basic, with naïve history mechanisms, linear undo and only basic session save commands. As these tools become better integrated with other tools and improve on their functionality then metavisualization and other intelligent exploration aids will be more necessary. Some recent work has been done looking at history trails, provenance and metavisualization but certainly more research is required in these areas if we are to meet the demands of the user in future. Finally, large screens are available today, but there is still a need to provide better navigation tools that work on these large displays and develop techniques that are specifically designed for CMV, and to merge and integrate the large displays with smaller hand-held devices.

7 Usability & Perception

It is possible to develop and create functional rich CMV systems that allow the user to initiate and coordinated many multiple-views, but are they usable? Baldonado et al. [7] in their seminal paper detail eight principles that a developer should consider: *Diversity* – that multiple views should be used when there are a diverse set of attributes, abstractions or genres; *Complementarity* – use

[2] http://www.9xmedia.com/

multiple views when they draw out correlations or disparities; *Decomposition* – partition complex visualizations into smaller manageable views; *Parsimony* – use multiple views sparingly; *Space/Time resource optimization* – there is a space/time trade-off and sometimes it's better to display sequentially in comparison to side-by-side; *Self evidence* – use perceptual cues to make the relationships more evident; *Consistency* – keep the interfaces consistent across views; and *Attention management* – use perceptual techniques to keep the user focused on the right view.

Recently researchers have started to perform more analysis on the usability and perception of results through multiple-view systems. For example, Plumlee and Ware [48] compare a multiple view system with zooming, while Convertino et al. [18] have looked at context switching in multiple views.

7.1 Summary: "Usability & Perception"

Researchers are now including usability studies with the description of their tools, but in many instances they seem to be afterthoughts with few test subjects and little detail presented. Although effective evaluation is still hard and time consuming it is required to work out what aspects of coordinated and multiple views are useful, what tasks they are best at addressing and how to develop effective solutions. Automatic recording software is available, but they generate massive amounts of data which are time consuming to analyze.

8 Conclusion

It is clear to see that we have come a long way. The CMV developer has many visualization forms to choose from, many interactive techniques to utilize and a large body of research to cite. But there is certainly much work to do and many challenges to overcome.

The use of CMV is changing and expanding, it is becoming part of larger sensemaking environments where the techniques are being used to analyze large datasets, integrate alternate viewpoints, and generate nuggets of information. Thus there are requirements to integrate more management and automation strategies to allow the user to effectively and intuitively collate, compare, hypothesize, manipulate and present their information. Users require CMV systems that are function rich yet intuitive and easy to use, quick to visualize the results, easy to look back at previous investigations. These present specific challenges to the system developer who needs to take care to create systems that are fully extensible and interoperable.

This paper demonstrates that over the past 15 years the subject of CMV has certainly developed and grown. Yet at times developers still forget the past and do not integrate all the possible rich interaction capabilities that have been in the literature for decades. Component and bean technologies will enable developers to move forward at a quicker pace and develop function rich applications that are based on previous well-established interaction and visualization capabilities.

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