Eyes + Device = Wise: Enabling Collaborative Visual Analysis of Big Data

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Abstract

Visual analysis involves leveraging visualization and visual analytics techniques for user-guided understanding of complex datasets. However, today's big data analytics problems require more than a single mind to solve. I tackle the challenges of multi-user (collaborative) visual analysis from two approaches: cross-device visualization platforms and interaction methods. In the former, I created platforms for developing cross-device visualizations including PolyChrome (a collaborative web visualization framework) and Munin (a framework for ubiquitous analytics). Building upon these platforms, I designed interaction models for visual analysis using gestural interaction and proxemics (spatial relationships between people in the physical space). I propose to further utilize these research contributions to understand the cognitive effects of device modality—size, input, and computing power—on visual sensemaking, and develop efficient human-data interfaces for collaborative visual analysis.

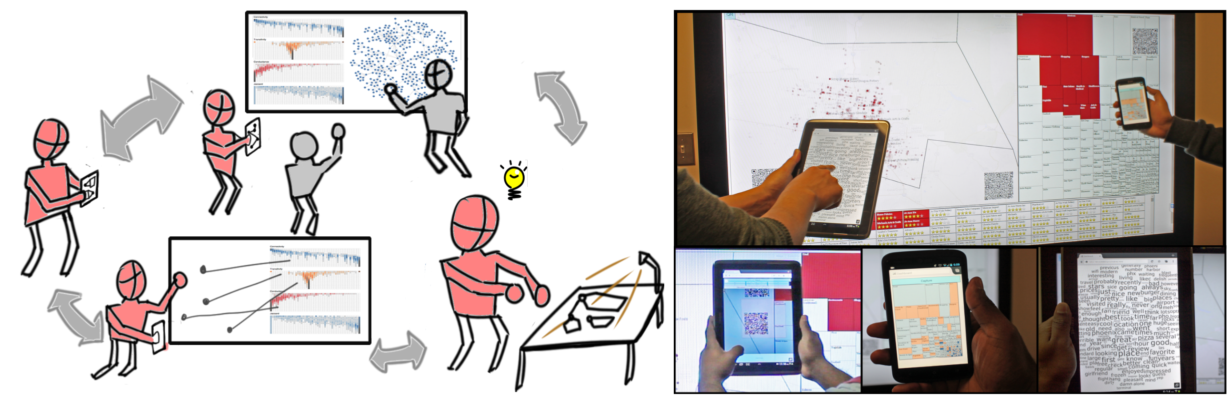

Figure 1: (Left) A collaborative visual analysis environment where users work with several connected devices to perform analytics. (Right) An example interaction model developed for such environments: analysts can capture visualizations by simply taking their picture (or rather a picture of the QR codes augmenting them), to interact with data across personal and public devices. This embodied interaction can enhance the productivity of the analysts by allowing them to work with any device of interest.

Introduction

The fields of visualization and visual analytics are starting to tackle big datasets arising from modern fields including scientific, medical, financial, social, and computing domains, through personal and collaborative sensemaking methods in co-located[1] and distributed spaces[2].

[1] W. McGrath et al. Branch-explore-merge: facilitating real-time revision control in collaborative visual exploration. In *Proceedings of the ACM conference on Interactive tabletops and surfaces*, pp. 235-244, 2012.

However, one of the major challenges faced in visual sensemaking is, how to leverage the innate abilities of the sensemaking environment containing large interactive surfaces, personal devices, and physical artifacts with different spatial relationships. My research goal is to *explore and understand how collaborative visual analysis of big data can be efficiently performed using an ecosystem of connected devices*. The core contribution from my research work will therefore be interaction models, cross-device platforms, and guidelines for collaborative visual analysis—one or more analysts working to generate insights from data. This work will support *ubiquitous analytics*[3] scenarios for interaction with data anywhere and anytime:

- A group of business analysts discussing a stock acquisition in an office meeting room. To start their conversation, one of the analysts shows some new projections for the stock markets that she has been working on, by pushing the visualizations on her tablet to a large display. While listening to her, other analysts pull the visualization onto their personal devices through an embodied gesture[4] recognized by environment—for e.g., by simply gazing at the public display. They then interact with the visualizations together to generate interesting insights and push them back onto the public display when needed for further consideration.
- Citizens of a city trying to resolve their urban issues. They use their phone to capture pictures of observed issues during their everyday activities. During a public meeting, they share the pictures onto a public display at the city square by simply taping their phones to the display, and interact with a geospatial visualization organizing the pictures on the city map. They categorize, prioritize, and resolve issues together through the interaction with the public display.
- A travelling couple at an airport. They see a billboard containing retirement savings visualization. They take a picture to grab it onto their phones. At the same time, one of them brings up data from their bank account including their monthly expenses, bills, and savings, onto a phone. They then work together on the flight to explore their options based on the retirement savings from the public display, by interactively merging the views on their phones while posing ``what-if'' questions: what if we put in $20,000 per year into the retirement fund.

These scenarios require appropriate hardware and software platforms, and interaction models that not only create a cross-device environment for collaborative visual analysis, but also intelligently operate across several device modalities, bridge physical and digital worlds, and ease complex visual analysis tasks. Therefore, the overarching goals of my dissertation include,

1. **Enable cross-device visualization and support collaboration.** To leverage multiple devices for sensemaking, this includes developing infrastructure for discovering, merging, and synchronizing heterogeneous devices for interaction with visualizations

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[2] K. Kim et al. Hugin: A framework for awareness and coordination in mixed-presence collaborative information visualization." In *Proceedings of ACM Conference on Interactive Tabletops and Surfaces*, pp. 231-240, 2010.

[3] N. Elmqvist and P. Irani. Ubiquitous analytics: Interacting with big data anywhere, anytime. *Computer* 46 (4): 86-89, 2013.

[4] P. Dourish. *Where the action is: the foundations of embodied interaction*. MIT press, 2004.

and sharing insights. Supporting multiple devices, by nature, extends to supporting collaboration among analysts working on the devices.

2. **Support multimodal interaction for visual sensemaking.** This involves designing and evaluating advanced interaction models [5] that go beyond the traditional WIMP (Windows-Icons-Menus-Pointers) interaction style, to leverage the physicality of the devices and analysts in the environment (post-WIMP). For example, analysts working on a large display combine their individual workspaces by walking close to each other, or start utilizing a smartphone as a personal workspace by pointing/taping it to the large display. These interaction models are universal (working with any device couplings), physical, and embodied in nature.
3. **Abstract and adapt visualizations and interaction styles**. Flexible visual representations are required to adapt to, 1) varying device dimensions, resolutions, and computing powers, 2) multiple interaction styles—mouse, multi-touch gestures, and physical interaction in 3D, and 3) visual analysis tasks involving exploration of overview+detail, focus+context, and individual+composite views, by assigning specific meanings to device modalities when needed (for e.g., using a smartphone to always overview the data while using a large display to show details). This guideline/goal eases the complex cross-device & collaborative visual analysis process, and improves experience and productivity.

Research Approach

I tackle these research goals through three phases covering distinct genres of research projects (not necessarily approached in a linear order).

Middleware platform development (SI): In this phase, I target development of software infrastructures for creating collaborative visual analysis environments containing large displays, tabletops, personal computers, portable devices, and sensing modules such as depth cameras. This includes platforms for managing the display space spread across the devices, synchronizing the user interactions across devices, and sharing observations and insights from visualizations among the analysts in the environment.

Hardware development (HI): This phase will target prototyping novel hardware infrastructures for visual analysis utilizing input technologies based on magnetic, capacitive, and depth sensing, and output mechanisms using projectors and stacked displays, to create appropriated interaction surfaces [6] that are built on existing physical artifacts in the environment. For example, this can involve turning a normal desk into an interactive surface using projector and magnetic sensing.

Interaction and application development (APP): During this phase, I target integration of the efforts from hardware and middleware development to build workspaces for collaborative visual analysis in different application scenarios and design post-WIMP interaction models for

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[5] J. C. Roberts, P. D. Ritsos, **S. K. Badam**, D. Brodbeck, J. Kennedy, and N. Elmqvist. Visualization beyond the Desktop--the Next Big Thing. *Computer Graphics and Applications, IEEE*, *34*(6), 26-34, 2014.

[6] C. Harrison. Appropriated interaction surfaces. *Computer*, (6), 86-89, 2010.

these workspaces. The interaction models will utilize implicit and explicit design patterns—interactions initiated proactively by the system while observing the users vs. interactions performed directly by the user—for visual analysis tasks in the environment. This phase also covers development of flexible visual representations.

Current Research

This section covers my current work including cross-device visualization platforms: Munin and PolyChrome, and interaction models based on proxemics and gestures for visual analysis.

Munin (SI – published in IEEE TVCG journal)

Munin[7] is a software framework written in Java for building multi-device environments consisting of multiple input and output surfaces, such as tabletop displays, wall-mounted displays, and mobile devices. This framework helps development of ubiquitous analytics spaces. Munin utilizes a service-based model where each device provides one or more dynamically loaded services for input, display, or computation. Using a peer-to-peer model for communication, the framework leverages IP multicast to replicate the shared state among the peers. Input is handled through a shared event channel that lets input and output devices be fully decoupled. The shared state, shared event, and service-oriented models for multi-device environments form the core philosophy of the Munin framework, promising a robust, fault-tolerant, decentralized system. However, the Munin framework faces issues in terms of the lack of support for high-level abstractions for visualization using Java, requirement to redesign services for different operating systems, and lack of persistent storage for asynchronous collaboration.

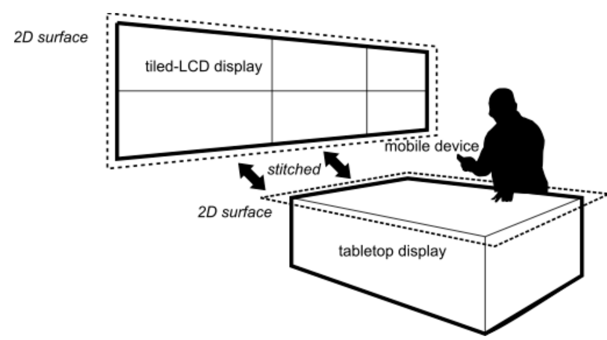

Figure 2: An example multi-device environment.

PolyChrome (SI – published in ACM ITS 2014)

PolyChrome[8] is a web application framework for sharing interaction and managing display space of various devices in collaborative settings. PolyChrome provides three distinct contributions to the community building collaborative visualizations, (1) **distributed web browser modules** to spread existing legacy visualizations on the web across multiple devices and share the user interactions across devices, (2) **interaction event and display space distribution mechanisms** (through a PolyChrome API) to create new cross-device, collaborative

[7] **S. K. Badam**, E. R. Fisher, and N. Elmqvist. Munin: A Peer-to-Peer Middleware for Ubiquitous Analytics and Visualization Spaces. *IEEE Transactions on Visualization & Computer Graphics*, *21*(2), 215-228, 2015.

[8] **S. K. Badam** and N. Elmqvist. PolyChrome: A Cross-Device Framework for Collaborative Web Visualization. In *Proceedings of the ACM International Conference on Interactive Tabletops and Surfaces*, pp. 109-118, 2014.

Figure 3: A web-based collaborative visualization of a scatterplot matrix created using PolyChrome.

web visualizations for multiple users and devices, and (3) **the ability to store the user interactions** for replay, conflict resolution, and consistency management. This framework is ideal for developing web visualizations for collaborative visual analysis, including the four combinations of synchronous vs. asynchronous and co-located vs. distributed collaboration.

Embodied Interaction for Cross-Device Visualization (SI + APP – in review)

Proxemics corresponds to the spatial relationships between people and artifacts in a physical space including their distance, orientation, position, and identity. During visual analysis in large display and immersive environments, the proxemics attributes can capture the user's intentions to perform visualization tasks such as showing details on the display when the user walks towards it, changing layouts based on user's orientation, and creating composite visualizations to enable collaborations between users close to one another. These implicit interaction opportunities are underexplored, compared to explicit gestural interaction. We developed an interaction technique called Proxemic Lens, for interaction with visualizations on large displays using focus+context lenses that are controlled through proxemics and mid-air gestures. An evaluation of these interaction models showed that users prefer proxemic interactions for navigation and collaboration, but prefer using explicit mid-air gestures to perform actions that are perceived to be direct, such as creating and deleting the focus+context lenses.

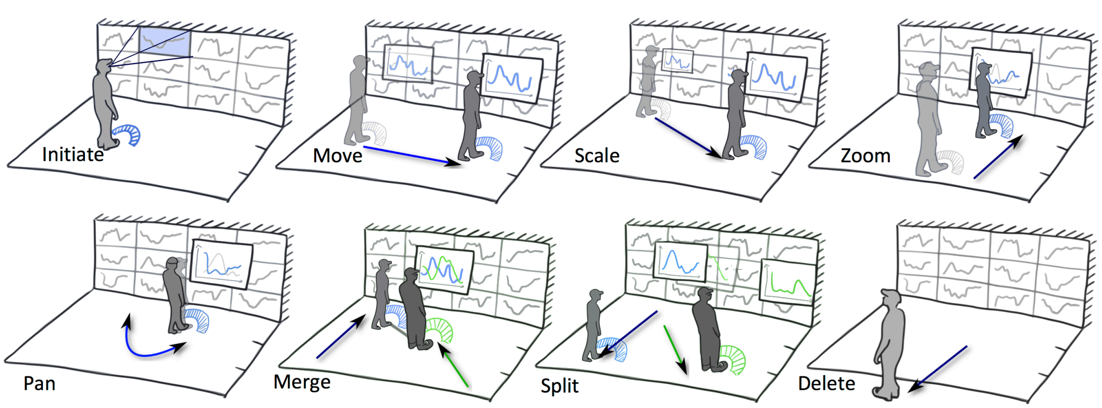

Figure 4: Design opportunities for implicit control of focus+context lenses in visualization through proxemics.

Going beyond a single-display space to leverage multiple devices—such as smartphones and tablets along with large displays—for visual analysis typically requires supporting extraneous operations for device discovery, interaction sharing, and view management. Such operations can be time-consuming and tedious, distract the user from the actual analysis, and are inconsistent with the natural interaction afforded by multimodal devices. We therefore developed Visfer, a technique (and framework) for effortlessly transferring visualizations and their dynamic state across devices using QR codes, which are captured by simply taking a picture with the built-in camera. This type of embodied interaction is essential for ubiquitous analytics scenarios described in the Introduction section.

Proposed Work

My current research work partially covers the first and second research goals of my thesis to some extent. To explore more complex interaction styles and develop flexible visual representations for collaborative visual analysis across devices, I propose three research projects. I plan to build upon the PolyChrome and Munin platforms to carry out these projects more effectively.

Cognitive Effects of Cross-Device Visualization (SI + APP)

Using multiple devices, such as large displays, tabletops, and portable devices, together for sensemaking may inhibit the analyst from exploring the full potential of these individual devices in the environment. This is due to presence of a variety of device modalities—input, output, and computing powers—which make it hard to easily switch between, say, interacting with a desktop computer using a mouse to performing multi-touch gestures on a smartphone. In visual analysis, the display dimensions, resolution, and orientation, also affect the usability of the visual representations, which are typically designed for a single device. Beyond this, the computing power creates added delays in visualizations on certain devices. For example, developing a visualization containing more than a million data points is now a standard process on desktop computers and high-performance devices, however, storing, rendering, and fitting them on a smartphone is almost impossible. These device tradeoffs have complex cognitive effects changing the productivity of the users in sensemaking.

I plan to evaluate and understand these effects of the device modalities in terms of, 1) quantitative measures such as time and accuracy, and 2) qualitative insights such as the ease with which different stages of the sensemaking process are carried out including hypothesis generation, making observations, and finding insights. For this evaluation, I will use visualizations of large datasets familiar to most people such as stock market data, movies, and traffic/flight patterns, to test different types of flexible visual representations designed to, 1) adapt to the display size by switching between dense and sparse visual representations, 2) adapt to interaction mechanisms by abstracting the input mechanisms (for e.g., navigating with a button click on a large display vs. navigating by physically tilting the device on a smartphone), and 3) adapting to the rendering powers of the devices by working with aggregated or sampled version of large datasets, or using progressive rendering models. By evaluating these design choices on different device modalities and cross-device scenarios, design guidelines for flexible visual representations can be developed to effectively use multiple devices for collaborative visual analysis.

SenseDesk (HI + SI + APP)

A major challenge of visual analysis across devices is setting up the environment (interaction space) itself. While typical office meeting spaces offer public displays for collaborative visual analysis, it is still a complex process to convert personal and group workspaces such as cubicles/desks into cross-device analytics spaces where the physical artifacts (e.g., pens and papers) and digital media (e.g., displays) can be used together. In this project, I therefore plan to focus on collaborative sensemaking in typical office workspaces by leveraging novel computing technologies for human-data interaction.

I propose to design, develop, and evaluate a platform prototype called SenseDesk for viewing, analyzing, and making sense of large and complex datasets at a typical office workspace (e.g., a desk or a cubicle). I plan to take a highly practical and engineering-oriented approach for augmenting a normal desk through a longitudinal iterative development process. During this process, I will first start with building a simple prototype with depth cameras and projectors that is capable of supporting my everyday computing activities (e.g., prototyping visualizations, writing reports, and attending video conferences). Following this, the desk will be evaluated and continuously improved by adding more features to bridge physical and digital artifacts, and support collaboration. For example, notes from a discussion between two researchers taken on a paper will be captured by the depth cameras and added to a meeting log. Finally, I will extend the system to collaborative visual analysis of large datasets (e.g., stock markets) by utilizing the features developed for everyday computing. The process of development of the SenseDesk will be continuously recorded (and will be made public), as it is as important as the SenseDesk itself. This process will involve understanding the caveats and limitations of certain hardware technologies, and overcoming them using complementary technologies.

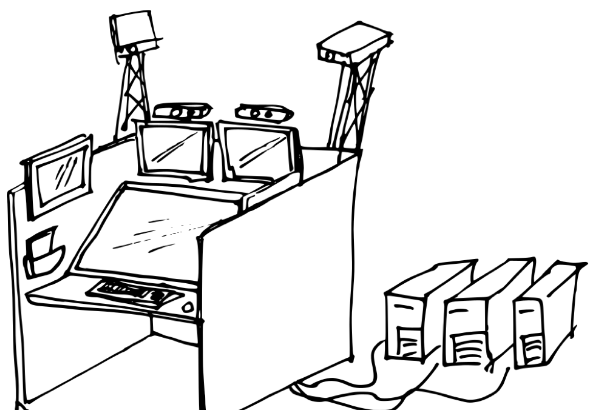

Figure 5: Sketch of the SenseDesk prototype.

Distributed Visual Analysis (APP)

Distributed collaboration covers collaboration scenarios where the users are distributed across multiple geographical locations. Supporting collaborative visual analysis across multiple devices in these scenarios requires approaches that bridge the disconnectivity among devices and users by visualizing the user activities alongside the actual visualization interface. These approaches, in essence, provide interaction ghosts (outlines of the user interaction) and virtual avatars to show the activities of the collaborators. In this project, I plan to design and evaluate context-specific ghosting mechanisms. In contrast to previous approaches that were mostly targeting large displays (will ample screen space), I plan to develop ghosting mechanisms for different display sizes and visualizations on the user interface. Examples include, 1) a smartphone can show the interaction of a collaborator through visual feedback on the borders of the visualization, while a large display can show it on the visualization itself, and 2) interaction ghosts for a line charts can be transparent lines representing the views of the collaborators, while bar charts can have simple markers on the bars themselves to represent the current view of a collaborator.

Benefits and Impact

Today's big data analytics requires more than a single mind and device for sensemaking. In this context, the proposed research can benefit the society working in domains that perform visual analysis such as scientific discovery, business analytics, classroom learning, and police investigation. By taking a comprehensive view towards development of hardware, software platforms, and multimodal interaction models for collaborative visual analysis, this work supports casual and expert users, both dedicated and mobile settings, and both small-scale and large-scale datasets. Furthermore, by exploring the design space of flexible visual representations, this work targets to improve user productivity in the visual analysis scenarios. Finally, in a broader sense, the interaction models and platforms from my proposed research can be embedded into the myriad of mobile and dedicated devices commercially available to enable cross-device interaction. For example, it should be possible to share a file between two devices by just flicking one's hand on one device in the direction of the other.